Design and evaluation of Nearly Zero Energy Buildings and their viability post-2013s UK climate conditions-

A collaborative research with The Chartered Institution of Building Services Engineers and Hilton.

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Declaration of Authorship:

I, Radwa Salem, declare that this thesis titled, ‘Design and evaluation of Nearly Zero Energy Buildings and their viability under current and future UK climate conditions’ was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or processional qualification except as specified

Signed: ...Radwa……………………………………………………………….

Date: ...29/05/2020……………………………………………………………..

Abstract

A candid endorsement of the scientific consensus regarding our changing climate has been corroborated in the reports of the Intergovernmental Panel on Climate Change (IPCC) and in the reports of major scientific bodies nationally and internationally. Paleoclimatology data, current climate data, and future projections unequivocally lead to the conclusion that for the past 50 years, our climate has changed because of anthropogenic activities. Consequently, the UK government is committed to reducing emissions by 80 percent, compared to the 1990 baseline, by 2050. Mitigation proposals have acknowledged that the building sector plays a vital role in contributing to the ambitious targets set for the transition towards an energy sustainable future. This is derived from statistics stating that the building sector is responsible for 40 percent of energy consumption across Europe. Depending on the building's electricity consumption, this figure can increase to more than 45 percent in primary energy and energy-related CO_2 emissions. The Fourth Assessment report of the IPCC has declared that 30 percent of anticipated emissions (within the building sector) can be prevented by 2030 with economic benefits.

Whilst the recast Energy Performance Building Directive (EPBD) has mandated that all new buildings should be nearly zero-energy buildings (nZEBs), including buildings that will undergo refurbishment/ renovations. The interpretation of how this will be implemented has been left for member states to decide. This open interpretation is inclusive of *what is a nZEB; how to achieve this*; *how much energy consumption and production exactly is 'nearly zero.'* This work therefore, investigates the current practices for designing nZEBs and explores how existing residential and commercial buildings can be retrofitted to achieve the standard. Thereby establishing a methodology that provides design solutions that meet set targets, whilst taking into consideration their performance under current and future climate conditions.

Studies have shown that the building industry is typically slow at adopting new technologies; despite their acknowledgment of the environmental benefits that technology can provide. The nZEB standard differs from other building energy efficiency methodologies that have been

proposed due to its focus on achieving the standard with cost benefits. The EPBD specifically stated that, in cases where a cost-benefit analysis of the economic lifecycle of a building is conducted and proven to be negative rather than positive, then the nZEB standard does not need to be applied. The selected designed or retrofitted nZEB building is typically defined as the cost-optimal scenario or solution.

It has been established that for most cities the number of existing buildings overshadows the possible number of new buildings. Correspondingly, the potential impact of existing buildings, in terms of energy consumption reductions, outweighs that of new buildings. Hence, this thesis focusses on the retrofit of existing buildings.

A quantitative research approach is utilised to address the research questions. The outcome of the research is based on real-life case studies and shows how the nZEB standard can be applied to those buildings in practice. The findings presented are based on analysis supported by dynamic simulation modelling of UK buildings, aiming to demonstrate the potential benefits but also highlight the risks associated with achieving such high energy efficiency standards within the built environment. Within this research dynamic simulation modelling is not just used for checking the primary energy consumption and carbon emissions, etc. but as a tool for designing and shaping the retrofit scenarios. The buildings are modelled as a baseline, with individual energy efficient measures, and as a complete retrofit with all the EEMs to help assess a wide range of potential scenarios before selecting the best option in terms of energy and cost benefits. This work also builds on the work presented in CIBSE TM38.

A variety of different real-life case studies are utilised to explore what it means to achieve the nZEB standard and apply it on existing UK buildings. They have been presented individually to focus on the various outcomes of each building type.

Table of Contents

List of Tables

List of Figures

List of Appendices

List of Acronyms/Abbreviations

ACH	Air change per Hour
ATB	Automatic Controlled Thermostat Boiler
ATES	Aquifer Thermal Energy Storage
AHU	Air Handling Unit
BRUKL	Building Regulation UK Part L
BRE	Building Research Establishment
BEIS	Department for Business, Energy and Industrial Strategy
BER	Building Energy Rating Certificate
BEEP	Building Energy Efficiency Policies
BLCC	Building Life Cycle Cost
CIBSE	Chartered Institute of Building Services Engineers
CEN	European Committee for Standardization
CO_2	Carbon dioxide emissions
SCATS	Smart Controls and Thermal Comfort.
C_G	Global Costs
CO_{INIT}	Investment Costs
CEC	California Energy Commission
CDD	Cooling Degree Day
CCL	Climate Change Levy
CoP	Coefficient of Performance
CFL	Compact Fluorescent Light
CHP	Combined Heat and Power
CCHP	Combined Cooling, Heat and Power
CHPQA	CHP Quality Assurance programme
DSY	Design Summer Year
DHW	Domestic Hot Water
DECC	Department of Energy & Climate Change
D_F	Discount Factor
DOE	Department of Energy
EDSL	Environmental Design Solutions Limited
EST	Energy Saving Trust
EEMs	Energy Efficient Measures
EPS	Expanded Polystyrene
EPC	Energy Performance Certificate

EPBD	Energy Performance Building Directive
EEP	Energy and Emissions Projection
FEES	Fabric Energy Efficiency Standards
FCU	Fan Coil Unit
FIT	Feed-in-Tariff
GBP	Green Building Programme
HVAC	Heating, ventilation, and air conditioning
H_a	Hours of Exceedance
HES	Hotel Energy Solutions
HDD	Heating Degree Day
HIPs	Home Information Packs
ITP	International Tourism Partnership
IES	Integrated Environmental Solutions
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LTHW	Low Temperature Hot Water Boiler
Low-e	Low-emissivity
LCCA	Life Cycle Cost Analysis
LCC	Life Cycle Costs
MV	Mechanical Ventilation
MVHRV	Mechanical Ventilation with Heat recovery
MURE	Mesures d'Utilisation Rationelle de l'Energie
nZEB	Nearly Zero Energy Building
nZEH	Nearly Zero energy Hotels
NPV	Net Present value
NCM	National Calculation Methodology
NREL	National Renewable Energy Laboratory
ONS	Office for National Statistics
PEC	Primary Energy Consumption
PV	Photovoltaic Panels
PTB	Programmable Controlled Thermostat Boilers
QI	Quality Index
RHI	Renewable Heat Incentive
RES	Renewable Energy Sources
SSSH	Self-sufficient solar house
SWH	Solar Water Heating

T_{upp}	Upper Temperature Limit
Tas	Thermal Analysis Software
TRY	Test Reference Year
UHI	Urban Heat Island Effect
VRF	Variable Refrigerant Flow
U-value	Thermal Transmittance
UKCP	United Kingdom Climate Projections
We	Daily Weighted Exceedance
ZCH	Zero Carbon Hub

بسم الله الرحمن الرحيم

I dedicate this thesis to

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for their constant support and unconditional love.

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List of Publications arising from this thesis:

Journal Publications

1. Salem R, Bahadori-Jahromi A, Mylona A, Godfrey P and Cook D. (2020). "Energy performance and cost analysis for the nZEB retrofit of a typical UK hotel." *Journal of Building Engineering,* vol 31, p101403. DOI: https://doi.org/10.1016/j.jobe.2020.101403
2. Salem R, Bahadori-Jahromi A, Mylona A, Godfrey P and Cook D. (2020). Life Cycle Cost Analysis of retrofit scenarios for a UK residential dwelling. *Proceedings of the Institution of Civil Engineers- Engineering Sustainability*, vol 173(2), p57-72. DOI: 10.1680/jensu.18.00055
3. Salem R, Bahadori-Jahromi A, Mylona A, Godfrey P and Cook D. (2019). Investigating the potential impact of energy efficient measures for retrofitting existing UK hotels to reach the Nearly-Zero Energy Building (nZEB) standard. *Energy Efficiency*, vol 12, p1577-1594 DOI: https://doi.org/10.1007/s12053-019-09801-2
4. Salem R, Bahadori-Jahromi A, Mylona A. (2019). Investigating the impacts of a changing climate on the risk of overheating and energy performance for a UK retirement village adapted to the nZEB standards. *Journal of Building Services Engineering,* vol 40(4), p 470-491. DOI: 1-22 DOI: 10.1177/0143624419844753
5. Salem R, Bahadori-Jahromi A. Mylona A, Godfrey P, Cook D. (2018) Comparison and Evaluation of the potential energy, carbon emissions, and financial impacts from the Incorporation of CHP and CCHP Systems in existing UK hotel buildings. *Energies.* vol 11(5), p 1219. DOI: 10.3390/en11051219
6. Salem R, Bahadori-Jahromi A, Mylona A. Godfrey P. Cook D. (2018). Retrofit of a UK residential property to achieve nearly zero energy building standard. *Advances in Environmental Research,* vol 7(1), p 13-28. DOI: https://doi.org/10.12989/aer.2018.7.1.000

Articles/Miscellaneous

7. Salem R. (2020). Net gains– retrofitting scenarios for net zero carbon, (available at: https://www.cibsejournal.com/technical/net-gains-retrofitting-for-net-zero-carbon/)
8. Salem R. (2020). CIBSE Research Insight – Nearly-Zero Energy buildings in the UK, (available at: https://www.cibse.org/knowledge/knowledge-items/detail?id=a0q3Y00000HwStTQAV#)
9. Salem R, Bahadori-Jahromi A - CIBSE ‘Grow your Knowledge’ (available at: https://www.gotostage.com/channel/3f4998a341254643b8a008df099a73f7/recording/c980e0d52e6841b3bea9369b623ce470/watch?source=CHANNEL)

Conference Papers

10. Salem R, Bahadori-Jahromi A, Mylona A. (2019). “Investigating the energy performance gap in UK residential dwellings,” Proceedings of international sustainability conference: Sustainability: Transdisciplinary Theory, Practice and Action (STTPA).

Chapter 1: Introduction

1. Introduction and Context

It is currently agreed that one of the major challenges in the construction industry is the energy efficiency and sustainability of buildings [Weiβenberger et al. 2014]. This, along with the prevailing paradigm of sustainable development means there is great emphasis on ensuring that buildings are energy sustainable.

The fifth legally binding carbon budget (CB2; 2018-2022) which aims to reduce carbon emissions by at least 80% below 1990 levels, by 2050, was approved by the UK government during 2016 [Carbon Budget Order, 2016/*785*]. Commercial property account for 13% of the UK built environment, contribute to 10% of CO_2 emissions and consume 7% of UK energy [PDR, 2017]. Generally, the building sector is the largest consumer of energy across Europe and is responsible for 40% of total energy consumption and 36% of CO_2 emissions, meaning that it plays a vital role in reducing projected increases in energy consumption and carbon emissions in the coming years.

In tandem with the carbon budget, the recast 2010 Energy Performance Building Directive (EPBD) requires all new buildings (including buildings that will undergo renovations) to be Nearly Zero Energy Buildings (nZEBs) [Directive 2010/31/EU].

Whilst the recast EPBD has set out a requirement for all new buildings to be nZEBs, it had only provided a generic definition and no specifications, for instance in terms of specific primary energy consumption targets, as to how this new concept should be implemented. Therefore, an open interpretation has been left for member states. Most importantly, the EPBD stated that, in cases where a cost-benefit analysis of the economic lifecycle of a building is conducted and proven to be negative rather than positive, then the nZEB standard does not need to be applied. It was also suggested that a 'cost-optimal' solution is selected for implementation.

The EPBD [recast] defines nZEBs as buildings that have a "very high energy performance… and the nearly zero energy should be covered to a very significant extent by energy from renewable sources" [Directive 2010/31/EU; EPBD 2013]. The EPBD's ambiguous definition means member states are required to develop clear and specific definitions that are in consonance with their national level of ambition, climatic conditions, and level of technology. Whilst some countries have begun establishing definitions, the UK has yet to release an official definition. However, in October 2019 an official public consultation was released to get this started. The aim was to future-proof homes with low carbon heating and world-leading levels of energy efficiency, by 2025.

Ideally the concept behind a nZEB means that it is an energy efficient building, with low energy demand, which employs a renewable/ microgeneration energy production system. However, in principle, certain traditional buildings reach the nZEB standard by incorporating an oversized renewable system. In a literature review study of nZEB definitions, Marszal et al. [2011] highlighted that a majority of the definitions reviewed considered only the incorporation of renewable energy sources, thereby neglecting the inclusion of energy efficiency measures (EEMs) to firstly reduce the energy demand of the building. Consequently, it was concluded that nZEB definitions should place emphasis on improving the energy efficiency of buildings. However, for most buildings this approach means incorporating several EEMs to reduce the energy demand. This in turn leads to an increase in the capital costs involved in reaching the nZEB standard and further complicates the issue of reaching the standard with 'cost-optimality.'

A 2017 study which analysed 411 nZEBs across 17 EU countries (using the zebra2020 data tool) showed that renovated buildings represent just 19% of the sample and commercial buildings only make up 36% of the sample [Paoletti et al. 2017]. Those percentages reflect the slow progress that is being made towards defining nZEB standard for commercial buildings, and particularly for existing buildings.

For most cities, the number of existing buildings overshadows the possible number of new buildings. Correspondingly, the potential impact of existing buildings, in terms of energy consumption reductions, outweighs that of new buildings. Moreover, seeing as more than 50% of residential buildings, within London, were built before 1971 [Itard et al. 2008], they suffer from deficiencies in energy performance. Therefore, even if such policies are fully implemented, it means reaching this target is an arduous task [UK-GBC, 2007], if existing buildings are not considered. The most recent amendment of the EPBD directive [Directive 2012/27/EU] has highlighted that the number of buildings being retrofitted “needs to be increased, as the existing building stock represents the single biggest potential sector for energy savings.” Once again highlighting that renovation of existing buildings is a key part of reaching energy efficiency on a wide scale.

From the issues raised above and review of relevant literatures, this research aims to explore and identify the key design factors that provide the largest contributions to a reduction in energy consumption and carbon emissions for UK residential and commercial buildings under current and future climatic conditions. Looking at nZEB exemplar projects throughout Europe and the UK one can see that although there are many buildings which have reached the ‘near-zero’ standard there have been no set method on how to achieve this. Most importantly, very few case studies have confirmed the proposed, typically high, investment costs are economically viable. Even when investors are presented with increased energy savings and thereby cost savings, they are often dissuaded due to the risks associated with the long payback periods; ebb and flow of energy prices; and unpredictability of the costs of new energy saving technologies. Thus, this research aims to investigate various cost-effective, routes to achieving the nZEB standard within residential and commercial buildings.

1.1. Gap in Knowledge

Based on the review of the current literature, the following areas have been identified to require further research:

1. **Key finding 1: Types of applicable EEMs utilised within UK nZEBs and their costs**

There is a lack of studies that investigate which measures and whole retrofit scenarios are realistically applicable for specific existing buildings whilst also considering costs and cost-optimality.

2. **Key finding 2: what is the nZEB standard and how to achieve it**

There is a lack of studies that aim to address what the UK nZEB standard means and no base approach/methodology available.

3. **Key finding 3: Cost-optimality of UK nZEBs**

Identifying what is a cost-optimal level for reaching the nZEB standard for UK residential and commercial buildings. According to the EPBD [244/2012] in order to carry out a life cycle cost analysis (LCCA) for a nZEB retrofit, EEMs should be individually selected and grouped into retrofit packages. Across the literature, no studies within the UK have utilised this suggested methodology by the EPBD.

4. **Key finding 4: Impacts of a changing climate on the nZEB performance**

There are no studies that confirm whether the achieved nZEB standard, under today's climate, is going to continue to perform up to the same standard under potentially different climatic conditions. If it is proven that the energy consumption of an established 'nZEB' building increases under different climatic conditions this could render the investment financially impractical, mainly due to increased operational energy costs.

5. Key finding 5: Risks associated with achieving the nZEB standard

The death toll of the 2003 heat wave in Europe exceeded 35 000 heat-related deaths. The elderly population were the most affected. The current paradigm within the construction industry in cold-dominant countries is to design/retrofit buildings with high levels of insulation. Whilst thermal comfort may be reached during colder months with this approach, the risk of overheating can be increased during hotter months. The basic principle behind a nZEB seems to have the potential to exacerbate this and there is a lack of studies that confirm whether the nZEB standard contributes to an increased risk of overheating.

1.2. Purpose, Direction and Significance of Research

The purpose of this work is to demonstrate how existing residential and commercial buildings can be retrofitted to achieve the nZEB standard. Thereby establishing a methodology which aids designers in coming up with adequate design solutions for UK nZEBs, whilst taking into consideration the influence of current and future climate conditions on performance of said buildings. For this work an adequate solution is one that is based on the nZEB definitions aggregated from the literature in combination with the findings of the cost analysis.

If the concept of nZEBs is implemented on a national scale in the future, it would mean there is a stabilisation of energy prices. Substituting current finite energy sources to renewable energy sources (RES) leads to a steadying of energy prices. This is because the cost of RES is reliant on the invested money and not the increasing or decreasing (or inflated) cost of the natural resource. Consequently, the amount of money being paid is only a small amount relative to the prices of current finite energy sources.

1.2.1. Research Questions

This work aims to answer the following questions that have been selected to address the identified gaps in the literature:

1. What are the types of EEMs that could be realistically applied to reduce the energy consumption in commercial and residential buildings?
2. To what extent is the residential and commercial nZEB retrofit technically and economically feasible?
3. What are the impacts of a changing climate on an achieved nZEB energy performance? And how does this affect the financial viability of the investment?
4. To what extent does retrofitting a building to the nZEB standard increase the occurrence and severity of overheating?

1.2.2. Aims and Objectives

The aim of this work is to investigate, through dynamic simulation, how to achieve the nZEB standard with economic benefits. The key objectives of each of the case studies included within this work are as follows:

A. To reduce energy consumption and carbon footprint in existing UK residential and commercial buildings

B. To model thermal performance of existing UK residential and commercial buildings against The Chartered Institution of Building Services Engineers (Cibse) current and future weather database and use the data to provide methods for retrofitting buildings to reach the nZEB standard whilst ensuring a constant building performance

C. To devise a matrix and a nZEB framework, providing methods of energy reduction and cost savings, tailored to specific building-types.

1.2.3. Delimitations and Selection of Case-Studies

Our modern society structure is complex, therefore, there are many different types of buildings that are utilised for different purposes ranging from office buildings to religious, educational, and retail buildings etc. Each building has its own energy, social and financial particularities and retrofit options that can and cannot be explored. For example, an automated lighting system can and is usually successfully applied in office and educational buildings and has been proven to generate significant energy savings. The same system, however, cannot be utilised in a hotel building in guest rooms due to issues of guest perception of privacy when it comes to automated systems. Similarly, whilst it would be possible to shut down parts of an office/school building and relocate the occupants in a temporary building; the same is not true for a hotel building. In addition, issues of noise and aesthetics whilst retrofit work is being carried out further restrict what can and cannot be done within settings that are centred around customer comfort. A fit-for-all solution is therefore not an option and to ensure that this thesis can provide focussed, tangible, and applicable outputs some delimitations have been set out as follows:

The term commercial building is used to a property where the activities taking place will result in a profit [DesignWiki 2020]. Commercial building application for this research is limited to hotels. To produce accurate, reliable, and valid models it is vital that all the necessary data and information of the case study is available. Data ranging from AutoCAD plans to energy consumption of commercial buildings is not shared and is considered very confidential. Therefore, to obtain such data would be very time consuming and may prove to be futile. However, as this is a collaborative research with Hilton, access to all the necessary data has been granted. Hotels were carefully selected to represent the typical UK hotel building stock.

High-rise residential tower blocks are not going to be considered: according to the 2018 English housing survey [MHCLG 2018], 85% of the UK population live in detached and semi-detached houses, therefore focusing on houses offers a larger representation of the current residential building stock. Furthermore, it is agreed upon that achieving the nZEB standard for a high-rise apartment block is considered *more* difficult as it presents more particularities. Therefore, to produce reliable and representative results we would need an in-depth study (even a different treatise) to tackle this effectively. High-rise residential dwellings for this project have been defined as any building that is more than 5-storeys.

Overall, the case studies were all specifically selected based on their potential to address the gaps found in the literature review and how representative they are of a particular building type. This was decided to ensure that the results can be generalised to as many existing buildings as possible. Table 1.1 provides justification for each selected case study. As can be seen from the table and as discussed above the case studies are selected based on their potential to address the research gap; therefore a specific assessment criteria such as certain U-values, glazing type, or no. of rooms/floors etc. was not set out. The research deals with real-life case studies and they are all very different. For this reason, there is no main assessment/selection criteria but rather each selected case study is unique and has its own research gaps, questions, and contributions individually. Please see Table 1.1 for full justification.

Table 1. 1: Justification of selected case studies

Case study	Addressed research question	Justification
Detached dwelling	Can a typical UK dwelling reach the nZEB standard?	According to the English Housing Survey [2018], 35 percent of the British population live in detached houses. Meaning that this type of dwelling is the second most common type of residential dwelling (with semi-detached being the most common) across the UK, thereby making it an excellent representative as a case study.
7 UK residential dwellings	What factors affect the performance gap?	Seven properties were specifically selected to represent all types of available residential houses in the UK. Only 14% of the UK population currently live in a flat or maisonette [MHCLG 2018]. Houses were therefore selected as they are highly representative of the UK building stock. It is important to include more than one case study for this investigation to gain an accurate insight into which factors affect the performance gap and to what extent their influence can be on this. Most importantly, the home-owner(s) were all willing to be interviewed. They provided details of their daily activities, such as their preferred heating set points, window opening schedule etc. so that the impact occupant behaviour

		has on energy consumption can be studied to assess the extent to which it is potentially a contributing factor to the energy performance gap.
Retirement village	What are some of the risks associated with reaching the nZEB standard? More specifically, does reaching the nZEB standard increase the risk of indoor overheating?	A retirement village was selected based on the review of the current literature which currently recommends mostly behavioural changes to address the risk of overheating and suggests that new retirement homes are at risk of overheating [Burns, 2008; Barnes et al. 2012; Guerra, Santin, and Tweed 2013, Lewis 2014; Kevin and Stephen, 2017]. However, behavioural changes are not always an applicable solution, especially in this case whereby the prototypical demographic of occupants are classed as part of the susceptible population to overheating.
Hilton Reading hotel	How can we utilise CHP and CCHP technologies in helping us achieve the nZEB standard?	To effectively investigate the potential of C/CHP systems a commercial building with high and constant occupancy rates, electric, heating, and cooling loads was necessary [DFIC, 2016; Jing et al. 2012]. Therefore, Hilton Reading hotel was selected as it has an occupancy rate of 90% and constant electric and heat demand and seasonal cooling loads.
Edinburgh Grosvenor Hotel	Can a historical commercial building reach the nZEB standard?	Based on the findings of the literature it was unclear whether older commercial buildings can reach the nZEB standard [Ascione et al 2017; Cellura et al. 2017]. As a result, Hilton Edinburgh Grosvenor hotel is selected as it is a historical building constructed in the 1860s.
Hilton Watford hotel	Can a typical UK hotel reach the nZEB standard?	The final selected commercial case study is a purpose-built hotel constructed in the early 1990s. This case study is selected as it is representative of the typical construction traditions of UK hotel buildings. Thus, the findings can be generalised to other existing UK hotels [Zangheri et al.2017; Tsoutsos et al. 2018].

1.2.4. Structure and Layout

- **Chapter 1 – Introduction to the work.**

The current chapter explores the scope of work and critically reviews the main issues and background of the nZEB standard. This chapter states the current gap in knowledge, establishes the research questions, objectives and lays out the structure of the thesis.

- **Chapter 2 – Literature review:**

This chapter is a review of the state of the art so far and begins by exploring how and why the concept of nZEBs emerged. The chapter offers a detailed review and analysis of the latest theoretical contributions and analysis on the topic of nZEBs.

- **Chapter 3 – Methodology**

The methodology chapter begins by setting out the research design and paradigm and the justification for selecting a quantitative methodology. Thermal analysis simulation combined with a life cycle cost analysis (LCCA) is going to aid in the investigation of how to reach the nZEB standard with cost-efficiency. Tas is utilised to initially validate the baseline models and then ensure that the retrofit scenarios do in fact meet the selected nZEB standard. The LCCA is carried out using building life cycle cost software (BLCC) to compute the life cycle costs (LCCs), net savings, and payback period. A sensitivity analysis is conducted identify uncertainty relative to the retrofit scenarios. The EPBD's cost-optimal range methodology is employed to select the cost-optimal solution. To investigate the risk of overheating associated with reaching the nZEB standard the CIBSE TM59 Overheating Criteria is utilised. All those different methodologies are explained in detail and step-by-step throughout this chapter.

❖ Chapter 4 – Residential nZEB case studies

This chapter explores all the residential case studies that have been modelled and investigated to explore the research questions. It presents the main results through various figures and tables; it then analyses and discusses the main findings to answer the research questions.

Case study 1: Bracknell detached house

This case study examines whether retrofitting a typical UK dwelling to the current nZEB standard is cost-effective for a homeowner with current available standard and cost of technology. The aim is to carry out a life cycle cost analysis (LCCA) to identify what is a cost-optimal level in terms of primary energy consumption (PEC) for a UK residential dwelling. In addition, the section investigates how best to achieve this by examining and focussing on the exploration of realistically applicable energy efficient measures (EEMs) and retrofit scenarios. Firstly, Thermal Analysis Simulation software (Tas, Edsl) is utilised to ensure the retrofit scenarios meet the nZEB standard's energy performance targets. The life cycle cost analysis (LCCA) is carried out by using building life cycle cost software (BLCC) to compute the life cycle costs (LCCs), net savings, and payback period. A sensitivity analysis is carried out to investigate the influence of various fluctuating variables and analyse which of those variables have the greatest impact on net savings and examine under which conditions do the nZEB retrofit scenarios increase in cost-effectiveness. Finally, the EPBD's cost-optimal range methodology is employed to select the cost-optimal solution.

Case study 2: Typical UK houses

This case study explores the various factors which could potentially contribute to the performance gap on seven different case studies one of which has been retrofitted to the nZEB standard. Thermal Analysis software (Tas, Edsl) is utilised to create a model that is a replica of the existing state of the different dwellings. Once the model is completed and simulated the energy consumption of the model is compared to the actual energy consumption. Subsequently, further simulations are carried out to examine the potential areas within the simulation that contribute to the largest discrepancy in energy consumption. This is of importance and relevance to the subject of this thesis due to the type of methodology utilised across nZEB studies which involves modelling of the building without any verification whether this modelled energy performance is a true reflection of the actual performance. Should recommendations be provided to investors just based on thermal analysis without considering the performance gap this will mean the retrofitted building will not perform as predicted and therefore the cost savings will be lower too.

Case study 3: Hughenden Gardens, retirement village

This case study is utilised to examine the impacts of a changing climate on the risk of overheating and energy performance for an existing UK retirement village. Homes within the retirement village share common characteristics, and therefore issues. Behavioural changes such as asking occupants to adhere to opening windows at certain hours are not always an applicable solution with this type of housing due to the prototypical demographic of occupants who are classed as part of the susceptible population to overheating. In tandem with this, the risk of overheating as a potential threat is exacerbated as it can lead to preventable loss of life. The buildings within the retirement village are designed to reach the nZEB standard with the currently recommended overheating mitigating strategies as obtained from the literature. Furthermore, because in overheating studies there is currently limited research regarding whether combined cooling/ heat and power (C/CHP) systems have the potential to act as mitigating strategies, to maintain the achieved nZEB standard and reduce the risk of overheating, they are investigated. CHP or cogeneration is an alternative method that utilises, by-product heat, which can amount up to 80% of total primary energy during electricity generation; meanwhile CCHP or trigeneration further utilises by-product heat to provide cooling. Consequently, the risk of overheating and energy performance of the various blocks within the retirement village as they currently stand and as nZEBs is investigated under current and future climatic conditions. The analysis is carried out using Tas and the CIBSE weather data files. The overheating criteria selected is the CIBSE TM59 Design methodology for the assessment of overheating risk in homes.

- **Chapter 5 – Commercial nZEB case studies**

Like the structure of the chapter above, this chapter introduces the commercial case studies investigated. It presents the main results obtained from the building modelling and the LCCA, where relevant. Selective tables and figures are utilised to support the discussion and analysis to answer the research questions.

Case study 1: Hilton Reading hotel

With an occupancy rate of 90% and constant electric and heat demand and seasonal cooling loads, the case study building, Hilton Reading hotel, is a suitable candidate for the comparison of CHP and CCHP systems. The purpose of investigating this is to determine the potential energy and economic benefits and penalties associated with the use of C/CHP within buildings and how these systems can be possibly utilised to bridge the gap between the technical and economic feasibility of nZEBs. Therefore, although a nZEB retrofit is not carried out for this case study, it still forms an essential contribution towards the recommendations and final outcomes of this project.

Part of the analysis involves the examination of the units under various climatic scenarios. These are based on future projections. For each scenario, there are three emission cases: 'Low', 'Medium', and 'High.' The projected emissions scenarios range from low-energy usage and carbon emissions to high fossil fuel usage and carbon emissions. According to the Climate Change Committee the 'Medium emissions' scenario represents a 'business as usual' increase in consumption of fossil fuels and carbon emissions and is selected for all time periods. The lifespan of C/CHP units are typically more than 15 years [MBS, 2016], therefore the weather files to be simulated are the 'TRY London' adapted to UKCP09 'Medium' scenarios for 2020s and 2050s projections.

Case study 2: Edinburgh Grosvenor Hotel

Currently within the UK there have been no investigations carried out to examine whether it is feasible to retrofit historical buildings to reach the NZEB standard. This case study therefore aims to investigate the potential for an existing 1860s UK hotel to reach the nZEB standard. The methodology adopted for this case study involves several stages. Firstly, Tas is utilised to provide an accurate prediction of the energy consumption, primary energy consumption (PEC), CO_2 emissions, building fabric and thermal performance of the building. To ensure validity of the baseline model, the modelling results are compared to the actual data of the building. Although this approach is time consuming in comparison to the typical methodology used across simulation studies (which usually involves validation of a reference model using a set database), it ensures that the study's outcomes are valid and applicable to other buildings of the same stock. Once the baseline model has been simulated and validated, the EEMs are individually simulated on the case study. Subsequently, the EEMs are combined to form sets of retrofit scenarios based on an iterative methodology, so that all the possible combinations of the selected EEMs are trialled.

Case study 3: Hilton Watford hotel

Once again there is a lack of investigation into the retrofitting of hotel buildings to the nZEB standard and analysing their energy performance and life cycle costs. Therefore, a nZEB retrofit is applied to the case study. Once again Tas is utilised estimate the energy consumption, primary energy consumption (PEC), CO_2 emissions, building fabric and thermal performance of the building and the actual building energy consumption is compared to the baseline model's energy consumption. Once the baseline model has been simulated and validated, the EEMs are combined to form sets of retrofit scenarios. Finally, a LCCA is carried out using building life cycle cost software (BLCC) and a cost optimal solution is selected using the EPBD's cost-optimal curve calculation methodology.

- **Chapter 6 – nZEB Framework**

The chapter ties in the investigations carried out on the different residential and commercial buildings. It begins by introducing a generic framework and then moves on to provide a detailed framework and decision matrix that aims to aid designers when it comes to retrofitting buildings to achieve the nZEB standard.

- **Chapter 7 – Conclusion**

In this final chapter the main summary of findings and recommendations drawn from the main 'Result and Discussion' chapters are presented. A discussion of how the research should be continued and limitations is offered.

CHAPTER 2: LITERATURE REVIEW

2. Chapter Introduction

This chapter begins by exploring how and why the concept of nZEBs emerged. Following this, the currently available definitions of nZEBs across member states and the current progress that is being made in UK and across member states to establish the standard is synthesised. The chapter moves on to explore and evaluate relevant methods to reaching the nZEB standard, including the life cycle cost analysis; discuss environmental implications of nZEBs and energy efficient buildings and their performance with regards to overheating; and identify key considerations to successfully retrofit existing building to reach the nZEB standards based on previous research. Finally, the chapter discusses the current work around developing suitable weather data files and how to select the most appropriate/relevant weather file based on the building being simulated and the question being investigated.

2.1. Origin of nZEBs

The 'Energy Performance Building Directive' (EPBD) was first introduced 4th January 2003. The directive stipulated that member states should implement the set out requirements of introducing energy performance certificates (EPCs), inspection of boilers, and inspection of air conditioning systems by 4th January 2006; and comply fully with specific articles 7, 8, and 9 by 4th January 2009 [BPIE, 2011]. The EPBD aimed to improve overall energy efficiency of buildings, which in turn would reduce CO_2 emissions and energy consumption contribution of the building sector.

Indeed, many countries including the UK adopted the directive. This introduced the 'Housing Act 2004,' 'Building Energy Rating (BER),' and 'EPCs' as part of the 'Home Information Packs' (HIPs). Despite this a recast directive was introduced on 19th May 2010 after it had emerged that the building sector still contributed to 40 percent of total energy consumption within Europe [Brian, 2011; Directive 2010/31/EU (recast)]. This time the purpose of the recast directive was to "strengthen energy performance required and streamline some of the [existing] provisions" from the original directive. It is specified that member states need to reduce total energy consumption from the building sector and increase usage of renewable energy sources. It is also this recast directive which introduced nearly-zero energy buildings (nZEB). More specifically article 9 stated that:

"Member States shall ensure that... all new buildings are nearly zero energy buildings and... new buildings occupied and owned by public authorities are nearly zero-energy buildings. Member States shall draw up national plans for increasing the number of nearly zero-energy buildings. These national plans may include targets differentiated according to the category of building." [Directive 2010/31/EU (recast)].

Whilst the recast EPBD does require all new buildings to be nearly-zero energy (nZE), including buildings that will undergo refurbishment/ renovations, the interpretation of how this will be implemented has been left for member states to decide. This open interpretation is inclusive of what is the nZEB standard; how to achieve this; how much energy consumption versus energy generation is 'nearly zero.' This leads to Article 2(2) of the directive which states that:

"[a] Nearly zero-energy building means a building that has a very high energy performance, as determined with Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby." [Directive 2010/31/EU (recast)].

Whilst 'Annex I' of the EPBD does not define specific standard performance as to what can be considered 'nearly zero energy'; it does specify design and retrofit aspects that need to be considered when calculating the energy performance of a building. These include heating, cooling, ventilation, building fabric, and lighting. Furthermore, in cases where a cost-benefit analysis of the economic lifecycle of a building is conducted and proven to be negative rather than positive then the nZEB standard do not need to be applied [Directive 2010/31/EU (recast)].

On 17th April 2018, the EPDB was revised and approved by the European Parliament [Directive 2018/844] once again. This update intended to reflect on the progress that has been made on nZEBs across member states and consolidate how the energy efficiency targets can be reached across Europe. The directive placed emphasis on the fact that member states must ensure that they have “clear guidelines and outline measurable, targeted actions as well as promote equal access to financing, including for the worst performing segments of the national building stock, for energy-poor consumers, for social housing and for households subject to split-incentive dilemmas, while taking into consideration affordability.”

Overall, the concept of nZEBs was introduced as a solution to the intrinsic environmental debt associated with most existing buildings.

A note on how Brexit affects this research: A spokesperson from the department of exiting the EU has stated that whilst this is an EU Directive, it has been included in the provisions of the Withdrawal Bill. It is also stated that on the issue of energy, emissions and buildings, the UK and the EU are continuing to work together towards a decarbonised low-emissions future – and this is not dependent on any ongoing negotiations over Brexit [PassiveHouse, 2017]. Furthermore, with its own ambitious energy and carbon targets, the UK government has already made clear what level of performance it requires from our future (and refurbished) buildings. For example, most recently, the government published a consultation document entitled “The Future Homes Standard: 2019 consultation on changes to Part L (conservation of fuel and power) and Part F (ventilation) of the Building Regulations for new dwellings.” The document sets out the plans for reaching new building standards with changes to Building Regulations in 2020 and 2025. The 2020 changes will be a partial step towards the planned 2025 standard whereby new dwelling energy performance will achieve a 75-80% reduction in carbon emissions over what is currently required by the Building Regulations Document Part L1A 2013. The consultation proposes two options:

1) a 20% reduction in CO_2 emissions achieved through very high fabric performance; triple glazing, gas-fired boiler and waste-water heat recovery (estimated cost increase of £2,500 per house);

2) [Government's preferred route] a 31% reduction in CO_2 emissions over 2013 requirements, achieved through small fabric improvements assisted by technologies such as photovoltaics (estimated cost increase of £4,850 per house).

The UK's latest official statement within the European Commission nZEB report corroborates this: *"The UK is progressing towards Nearly Zero Energy Buildings through incremental increases to the energy efficiency of the buildings required by building regulations. These are driven by national policy objectives to reduce both carbon dioxide emissions and energy demand in buildings, with the aim of setting standards for the delivery of 'zero carbon' new buildings."*

2.2. nZEB Case Studies

Understanding the energy performance of previous and current case studies is an important step towards achieving a nZEB. By studying different examples, useful and relevant information can be extracted to guide and meet the research questions of this work.

2.2.1. Residential nZEBs

One of the earliest (if not first) examples of a 'nZEB' is developed by the 'Fraunhofer Institute for Solar Energy Systems'; whereby they built what is known as "an energy autonomous house" [Voss et al. 1996; Vale and Vale. 2000]. From 1992 to 1995, the house located in Freiburg, Germany, is a 'Self-Sufficient Solar House' (SSSH). The house met all its energy demands purely by relying on solar energy. To counteract the mismatch between solar radiation input and energy demand during winter (and generally, due to Germany's cold-dominant climate with moderate solar radiation) energy saving technologies were implemented in addition to the "highly efficient solar systems" [Voss et al. 1996]. In more detail this was achieved via decomposition of water leading to a solar generated hydrogen energy storage which acts as a "cogeneration plant." Now, the building is used to research "fuel cells as small CHP units for building heat and electricity supply" [Voss et al. 1996].

Similarly, in Germany (Flieden, Hessen), the 'Solar Plus Haus' was constructed in 2006. Interestingly, this nZEB has implemented a wind turbine as a RES [Hurt et al. 2006]. Many nZEBs abnegate from the use of wind turbines due to many reasons such as noise pollution; aesthetically displeasing; wind strength may be too low (particularly in non-coastal/hilly areas); and safety concerns [Philips et al. 2007]. Yet this project successfully demonstrated that they may be used even with residential Buildings. Other energy systems ranged from mechanical ventilation to photovoltaic (PV) panels and triple glazed windows.

A 2015 cost optimality assessment of a single-detached dwelling located in Northern Italy explored and analysed “40 economically and technically feasible energy efficiency measures” [Paolo et al. 2015]. Interestingly, the study compared the difference between achieving a near-zero and a net-zero standard. Findings concluded that reaching the near-zero standard is much more easily achieved and more compatible with existing buildings. In more detail, the study stated that reaching the near-zero standard can be achieved with “adding a large number of PV panels, and with advanced technical systems such as heat pumps,” or with increasing insulation and improving the main technical systems such as gas/ boilers etc. Finally, the study concluded that “technically optimal” solutions were not “economically optimal” and that it is essential further studies focus on decreasing this gap.

An economic and computational study conducted in 2010 investigated “the potential of achieving thermal comfort and delivering electrical demands for existing buildings on site” [Attia, 2010]. Various integrated passive and active design strategies were incorporated in the retrofitting of a chalet, located in Ain-Sokhna. The results of the study concluded that some of the strategies implemented for retrofitting were cost effective with a payback period of 2 to 7 years. Meanwhile, other measures were not cost effective at all due to the long payback period of 19 to 41 years. Methods that had short payback periods included the ‘Compact Fluorescent Lighting’ (CFLs) and the thermosyphon solar collector to meet ‘Domestic Hot Water’ (DHW) needs [Attia. S, 2010]. On the other hand, the following measure were not cost-effective due to the long payback period.

- Wall external thermal insulation (U-value= 0.234 $W/m^{2°C}$)
- roof insulation (U-value= 0.177 $W/m^{2°C}$)

- double pane low-emissivity (low-e) windows
- 1.1-kilowatt peak (KWp) PV system and a small-scale wind turbine.

However, it is proven the retrofitting process provided thermal comfort for its occupants and met the project's zero energy goal [Attia, 2010].

2.2.1.1.Overheating in Residential nZEBs

Various definitions of overheating exist in the literature. The Cibse TM59 design methodology [see section 3.4 for more detail] defines overheating as bedroom temperature that exceeds 26^{0}C in bedrooms from 10pm-7am for more than 1% of occupied hours per year. The UK is known for its relatively mild winter and temperate summer climatic conditions. During the past 30 years London has exceeded 26.1^{o}C for less than 1% of the time [Cibse, 2015]. Consequently, the use of non-passive cooling techniques is uncommon, meaning buildings are not designed or equipped to cope with any rise in temperatures.

The effects of this is seen when weather abnormalities such as heatwaves occur during the summer months. The death toll of the 2003, 2006, and most recently the 15-day peak of the heatwave in June and July 2018 is 20,000+, 680, and 650+, respectively [Kovats et al. 2006; HPA, 2008; Carrington and Marsh, 2018]. Each year it is concluded that "the people most at risk in a heatwave are the frail elderly" [Age UK, 2015]. A report published in July 2017 also corroborated the fact that the UK is "woefully unprepared" for heatwaves and it is predicted that unless action is taken the death toll will rise to 7000 a year by 2040s for heat-related deaths [Christidis et al. 2014; Carrington and Marsh 2018]. The population of over 75s has also been projected to nearly double in the next 30 years meaning there will be an increase in the vulnerable population who are unable to acclimatise due to various physiological and cognitive impairments prevalent within this population demographic [Kenny et al. 2010; Gasparrini et al. 2012; ONS, 2014; PHE, 2014]. This is particularly applicable for residents in retirement homes [NAT, 2017]. As a result of this, a retirement village case study is selected as one of the buildings investigated for this work.

Because the general existing UK residential building stock tends to be poorly insulated, overheating at the moment is typically not an issue and currently the death toll due to low indoor winter temperature in England and Wales exceeds the heat-related death toll by 98% [Klenk et al. 2010]. Nonetheless, as mentioned previously by 2040 it is estimated that the temperatures experienced in the UK during the summer of 2003 will be the norm and it is expected that this will cause a drastic shift in those percentages.

Pathan et al. [2017] investigated the risk of overheating in London by monitoring 122 properties during the summers of 2009 and 2010. It is concluded that "London dwellings face a significant risk of overheating under the current climate." In their review of overheating in new UK homes Dengel and Swainson [2010] found that there is growing evidence that high energy efficiency standards (i.e. high levels of insulation without appropriate ventilation) lead to overheating and can also negatively affect the health of occupants. Several studies have concluded that new-build care and retirement homes are already at risk of overheating [Burns, 2008; Barnes et al. 2012; Guerra, Santin, and Tweed 2013, Lewis 2014; Kevin and Stephen, 2017; Salem et al. 2020].

A UK study investigated summer temperatures in 224 dwellings found that pre-1919 dwellings were least likely to overheat; meanwhile post-1990 dwellings were most likely to experience overheating. It is suggested that this is largely due to the difference in construction, mainly, the levels of insulation and airtightness [Firth and Wright, 2008]. A similar notion is established by a 2013 study which found that pre-1919 dwellings were significantly cooler whereas post-1990 dwellings were significantly warmer. Bedrooms in particular seemed to experience overheating even during cooler summer temperatures [Beizaee et al. 2013]. Once again Hulme et al. [2013] confirmed that modern (1975-80) properties with an energy efficient SAP rating of 70+ and post-1990 dwellings were warmer whilst pre-1919 dwellings were cooler.

The introduction of the concept of nZEBs alongside the 2050 carbon budget led to a shift in the design paradigms within the construction industry across Europe which means that new and existing buildings are expected to be energy efficient.

New homes are therefore being designed to satisfy the demanding requirements of new regulations whereby high levels of insulation is incorporated amongst other measures to ensure the energy demand of the building is lowered. Additionally, existing buildings are being retrofitted to catch up to the energy efficiency standard of new homes. The basic concept behind the nZEB standard exacerbates the risk for overheating in homes under hotter weather conditions [Sameni et al. 2015]. Despite this there is very little research and investigation regarding the issue and the potential of the widespread implementation of the nZEB standard across Europe to compound the risk of overheating in buildings.

Increasing population has meant that the proportion of apartment type buildings being developed has increased by at least 50% across the UK and 80% in London. Although this practice allows efficient use of land by increasing the number of dwellings which can be built per unit area, research has shown that flats have a higher risk of overheating [Carrilho et al. 2012; Porritt et al. 2012]. This is largely because typically the level of ventilation that can be achieved with this type of dwelling is smaller in comparison to houses for example.

The average number of Cooling Degree Days (CDD) has more than doubled in London alone between 1961 and 2006. Meaning that the amount of energy required for cooling has increased and is continiuing to increase as temperatures rise. Despite this summertime heat gains are still neglected in both nZEB studies and real-life applications for new and existing buildings being retrofitted [Sameni et al. 2015].

Peacock et al. [2010] investigated internal temperatures of dwellings using dynamic thermal simulation and predicted based on findings that, by 2030, 18% of homeowners will install air conditioning in response to increasing temperatures. Meaning that in London alone more than 500,000 homes will have air conditioning. This would not only lead to difficulties in meeting the 2050 carbon target but would directly hinder any progress being made towards reaching the nZEB standard.

Roaf et al. [2009] explored the advantages of utilising passive ways of reducing the risk of overheating in homes built to a high energy efficiency standard and concluded that this is an effective way to mitigate the risk of overheating. However, as previously mentioned, for flats, there is limited opportunities for the incorporation of natural ventilation due to the physical characteristics of such buildings. Another physical building characteristic which seems to influence overheating is the orientation of the building as established by Pana [2013]. The orientation of the building is an interesting factor to influence whether a building experiences overheating but is limited in terms of applicability as altering the orientation of existing buildings is not possible. Nonetheless some studies suggest that incorporating external shading can help maintain summer thermal comfort [Schnieder, 2009; Carrilho et al. 2012]. Flats located at higher floor levels were also found to be more likely to experience overheating [Baborska-Narożny et al. 2015; Jenkins et al. 2014]. Carrilho et al. [2012] used dynamic thermal simulation to investigate the technical and economic feasibility of the nZEB standard in a mild southern European climate zone, Lisbon, on two houses with different levels of glazing (moderately glazed and highly glazed). They found that high levels of glazing contribute to an increase in the risk of overheating. For example, the living room temperature in the highly glazed house exceeded 28°C for more than 46% of the summer season.

The above signifies that to maintain thermal comfort applied EEMs should ideally achieve a balance between the heating and cooling demand throughout the year. Therefore, whilst the application of high levels of insulation remains necessary during the heating season, consideration must be given to the building performance during the non-heating season through the application of adequate (active or passive) cooling strategies.

2.2.2. Commercial nZEBs

As part of the European initiative 'Nearly Zero Energy Hotels' (neZEH) 16 hotels across Europe were provided technical assistance to undergo refurbishment and reach the NZE standard. Located in Rethymnon - Crete, Greece, the Ibiscos Garden hotel is one of the 16 pilot case studies aiming to reach the NZE standard [neZEH, 2017]. The initial implementation of solar thermal heating followed by an increase of 50 percent of its solar storage tank, means that all the hot water consumption within the hotel is now met by renewable means. One of the interesting actions to be undertaken is the "energy upgrading of kitchen equipment" [Tassos, 2017]. According to 'Hotel Energy Solutions' (HES) preparing meals is one of the main energy consuming activities in a hotel after heating including hot water, cooling, and lighting [HES, 2011]. This is corroborated by the 2017 Hotel Data Conference, which presented that on average 'room heating/cooling and hot water' make up 63 percent of energy consumption, following this is 'kitchen' which makes up 11 percent of energy consumption [HNN, 2017]. Whilst it may seem difficult to control this type of energy consumption, the upgrading of the equipment used is a very simple yet effective way to reduce kitchen energy consumption.

The Alpine mountain refuge 'Schiestlhaus,' Hochschwabgruppe, Austria is one of the thirty case studies analysed by the 'International Energy Agency' (IEA) for their nZEB research [François et al. 2017]. Due to its unique location, particularly the high altitude, and its south facing orientation it can rely on solar thermal energy to heat water and a photovoltaic system to generate electricity. One of the simplest yet very cost-effective measures incorporated is Greywater recycling. The specific system used by this hotel is 'Greywater Recycling On-Demand' as opposed to the batch system. This system is very compatible with hotels due to its space saving and fast payback period [Siobhan, 2016]. On average, this saves up to 24 percent of mains water each month.

In terms of technical feasibility Tsoutsos et al. [2018] presented the actual primary energy consumption decrease of six southern and one northern European hotel that were part of the neZEH project. The results proved that a 'dramatic' decrease in the primary energy consumption

(PEC) is achievable with an average reduction of 63% amongst the examined hotels. It is noted that activities that do not directly involve guests were more critical in terms of reducing the PEC.

A paper which aimed to assess how achievable the nZEB standard within the hotel sector in Southern Europe is, concluded that whilst the nZEB vision "in hotels is close to reality" and can be economically attractive it remains challenging due to hotel buildings' individualities and therefore complexities [Tsoutsos et al. 2018]. Most commercial buildings typically have fixed operating hours whereas hotels can operate around the clock. This adds to the complexity of identifying energy use patterns.

Similarly, Zangheri et al. 2017 investigated reaching the nZEB standard on several reference buildings from various countries. It is found that there appears to be a pattern between the nZEB building regardless of location. For example, the nZEB building typically has high levels of insulation, double or triple glazing (depending on local climate), an efficient boiler or ground source heat pump (GSHP) and a renewable solar system. However, whilst it is noted that the nZEB retrofit did not vary significantly, the same could not be said for the cost-optimal benchmark. Furthermore, it is difficult to reduce global costs (energy, investment, replacement, and maintenance costs) whilst ensuring the standard is fully met. They also highlighted that one of the most significant barriers to obtain a valid and reliable cost analysis is the collection of reliable data for the renovation costs.

Across Europe various studies have considered whole-building retrofit on existing/reference case studies to reach the nZEB standard. However, most of the current literature considers residential buildings, with very few studies focussing on commercial buildings; particularly historical/older buildings which tend to be more challenging to retrofit. Loli and Bertolin [2018] highlighted the need to consider "minimal technical interventions" when retrofitting buildings of historical importance. Considering that certain case studies used within this research have a listed building consent requirement (i.e. they are of special architectural/ historical interest) it is essential that the retrofitting scenarios explored do not include redundant refurbishment of the building fabric. Meaning that where possible it would be best to work with the existing fabric or ensure that any improvement is justified in terms of the energy and cost-savings it has to offer and that it does not alter the current appearance of the building.

A similar notion is established from a study in Italy which explores whether the retrofitting of a historical educational building is feasible. Ascione et al. 2017, concluded that whilst significant energy, economic, and environmental savings are achievable; heritage buildings present more particularities and offer less flexibility regarding the type of energy measures which can be incorporated. Correspondingly, the redesign of a rural building in a heritage site located in Italy to reach the nZEB standard found that 'invasive' measures could only be justified in the case of insulation due to the high energy savings achieved. The results also showed that the best performing solutions were those with "limited invasiveness" such as lighting [Cellura et al. 2017].

2.3. Defining nZEBs

Whilst the EPBD (recast) provides a generic definition for nZEBs; a widely accepted and distinct harmonised definition does not exist [Kosmopoulos and Papakwstas, 2012]. Moreover, recognising the different climatic and local conditions of member states, the EPBD once again does not provide specific requirements (i.e. in kWh/m^2/y) for nZEBs. These, together with the absence of a standardised calculation methodology for energy performance, leads to a disparity in the approach undertaken to achieve a nZEB amongst member states [Marszal and Heiselberg, 2009]. Furthermore, in certain cases this has led to "national targets based on the concept without a clear definition" [Karsten et al. 2010; Kosmopoulos and Papakwstas, 2012].

Although commercial definitions of nZEBs do exist they tend to be limited and/or biased [Karsten et al. 2010; Marszal and Heiselberg, 2009]. For instance, even though it is recognised that an annual nearly-zero energy balance is not acceptable as a standalone requirement to classify a building as nearly zero energy, many commercial definitions define them as such [Marszal and Heiselberg, 2009]. Another example would be considering only thermal or electrical needs to achieve the balance. In other cases, energy inefficient buildings were classified as nZEBs due to their use of "oversized [photovoltaic] PV systems but without applying relevant energy saving measures" [Karsten et al. 2010; Voss et al. 2012]. Moreover, these definitions do not take into consideration the interaction of the building with energy grids; although this is a standard recognised requirement for a building to be classified as a nZEB. [Sartori et al. 2010; Voss et al. 2012] Consequently, these definitions cannot form an adequate standard that can be used for regulations and policies.

According to Lewis [2009], the fundamental concept behind nZEBs is that the building should meet most of its energy needs via low cost renewable energy sources (RES). Ideally, a nZEB therefore needs to have a low annual energy use that balances with the generated renewable energy.

2.3.1. Commercial nZEBs

Regarding the implementation of commercial nZEBs on a national level, several Member States have released a form of plan or definition to guide the progress towards achieving nZEBs. However, according to D'Agostino et al. 2016 "many of the national plans have missing or vague information," with many definitions missing numerical targets. Moreover, many of those definitions have only focussed on establishing a standard for residential buildings, leading to negligible progress towards defining the nZEB standard for commercial buildings. Generally, across Member States there is also a lack of explicit and detailed policies relating to nZEB refurbishment. Furthermore, many Member States tend to have a common nZEB definition for both new and retrofit nZEBs, however, it is important that they are differentiated due to the inherently distinct characteristics of new and existing buildings. Many of the works analysing progress on nZEB definitions have concluded that the absence of this differentiation remains a significant impediment [Marszal et al. 2011; Sartori, Napolitano, and Voss, 2012; D'Agostino et al. 2016].

Finding a common definition for nZEBs on a European scale is an arduous task due to the flexible outline of the recast EPBD which lacked numerical targets and allowed Member States to define their own standard because of the differences between local climatic conditions, level of building technology, building traditions, and level of ambition. Accordingly, between European countries nZEB definitions vary significantly and are difficult or impossible to compare. Thus, it would not be ideal to apply nZEB definitions interchangeably across European countries.

Annex I of the EPBD states that "the energy performance of a building shall be expressed in a transparent manner and shall include an energy performance indicator and a numeric indicator of primary energy use, …". It also highlighted that whilst countries can use other indicators, they must not neglect setting a specific value for the PEC. Based on this, it has been recommended that the energy performance indicator should be stipulated as "energy needs for heating and cooling" [Kurnitski, 2013]. This means that lowering the energy demand of the building is necessary. As for the primary energy use for this thesis, the total PEC will be considered on an annual basis. Consequently, the main indicators to be used throughout the thesis to assess whether the building has reached the nZEB standard will be the PEC and CO_2 emissions. As for the energy consumption although its results will be investigated, it will not act as an indicator seeing as there is no specific requirement in the EU directive (and as a result in any of the currently available nZEB definitions) that require a specific energy consumption of the building.

Looking at the currently available definitions across Europe, the RT2012 national law released in France stipulates a PEC of 110 kWh/m^2/yr or lower for new commercial nZEBs [Roger et al. 2013]. In comparison to this, Austria's OIB Directive 6 national law specifies a PEC of 170 kWh/m^2/yr or lower in commercial nZEBs [AEA, 2010]. Meanwhile, in June 2015, Italy released the DM 20 national law which outlines a calculation method whereby the PEC of a nZEB should be calculated based on a reference building; it also presents "a minimum rate of renewables" to include heating, DHW, ventilation, lighting, cooling, and movement of people (lifts) for commercial nZEBs [CAE, 2013]. The UK still has not released an official definition for commercial nZEBs.

However, several databases across Europe have been developed with the aim of presenting vital building information to drive progress towards a low-carbon future. Examples include the Zebra2020 data tool, Building Energy Efficiency Policies (BEEP), Green Building Programme (GBP), Mesures d'Utilisation Rationelle de l'Energie (MURE). Out of the available databases a possible solution to defining the nZEB standard for a UK commercial building where there is a lack of official definition would be to utilise the tools developed by the zebra2020 project. The EU zebra2020 project was launched in 2014 with the purpose of presenting nZEB building indicators and establishing strategies to resolve barriers to reaching the nZEB standard across Europe. The project synthesised data from numerous nZEB case studies which allowed a quantitative and qualitative analysis on the performance and key characteristics of successful nZEBs across Europe to be carried out [see Appendix A].

The tool is divided into three sub-tools. In more detail, the first part of the tool is called the 'Data Tool,' and it provides a summary of the existing building stock by country and aims to "overcome data gaps" by offering detailed information regarding the transition towards nZEBs. The second part of the tool is the 'nZEB Tracker' which offers building information for existing successful nZEB case studies and their relevant indicators such as the primary energy performance, passive and active energy efficient solutions and types of renewables utilised. The tool separates those indicators for residential and commercial buildings and the information is presented by country. Therefore, the tool is used to aggregate a definition with numerical targets specific to UK commercial nZEBs and is based on successful existing UK nZEBs that are currently in use [Table 2.1].

Table 2. 1: Building fabric, energy consumption, primary energy consumption and carbon emissions of the commercial nZEB target

	Commercial nZEB Target
Wall (W/m^{2}K)	0.11
Floor (W/m^{2}K)	0.10
Roof (W/m^{2}K)	0.15
Windows (W/m^{2}K)	0.92
Air permeability rate (m^3/h/m^2 @50Pa)	2.00

Primary Energy Consumption (kWh/m²)	At least 60% reduction in PEC
Carbon Emissions (Kg/CO_2/m²)	At least 50% reduction in annual Carbon Emissions

2.3.2. Residential nZEBs

For this work the definition to be used to classify a building as a residential nZEB will be aggregated from the official UK Primary Energy Consumption (PEC) target, in combination with the targets developed by ZCH combined with the findings of the Zebra2020 project. Since 2008 ZCH has worked with the UK government and industry to create a standardised definition for nZEBs which can then be used by the building sector industry [DCLG, 2006-2009].

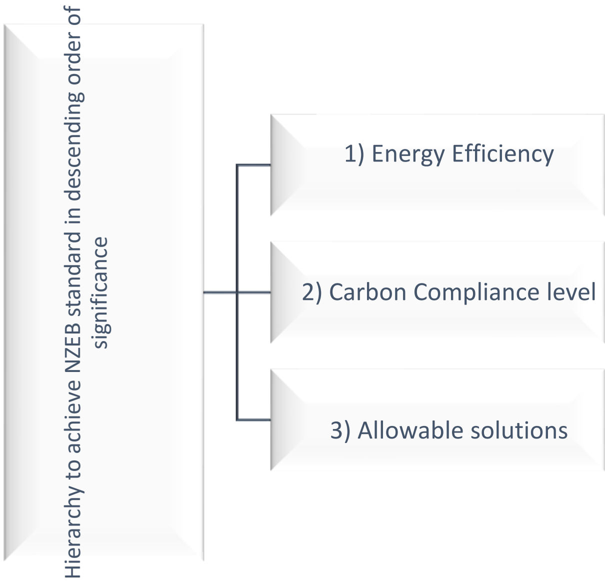


Figure 2. 1: Reproduced figure of government's preferred hierarchy to achieve N/ZEB standards (ZCH, 2009)

As can be seen from Figure 2.1, ZCH has set out a hierarchy to achieve the standard. Within this, energy efficiency is the prime issue which needs to be addressed. This focuses particularly on the energy efficiency of the building fabric. 'Fabric Energy Efficiency Standard' (FEES) compliant homes mean that a comfortable internal temperature is maintained. The FEESs' specify the "minimum level for overall fabric performance" required to achieve a nZEB. It is essentially the maximum calculated energy required for a house to maintain internal comfort conditions. It does not consider systems' efficiencies, building services, fixed lighting, ventilation strategy or the nature of the fuel used; but rather the fabric U-values, thermal bridging, thermal mass, and features affecting lighting and solar gains [ZCH, 2009].

The subsequent factor to take into consideration is the 'Carbon Compliance.' The current average carbon emissions per household in the UK is 26 kg CO_2/m^2/year [CCC, 2016]. Once the fabric performance has been taken into consideration, any residual CO_2, "must be less than or equal to the carbon compliance limit" set by ZCH. For a detached house, this compliance level is set as 10 kg $CO_{2(eq)}/m^2$/year. Whilst this may seem challenging, ZCH reiterated it is deliverable [ZCH, 2013].

Finally, by means of 'allowable solutions,' any CO_2 emissions remaining after achieving carbon compliance (which "cannot be cost-effectively off set on-site"), are offset via "nearby or remote measures." The allowable solutions to be investigated throughout this thesis will include 'on-site' options such as electricity storage for PV panels to investigate its effect via simulation.

Although ZCH has ceased operation since mid-2016, which was a direct result of the government no longer pursuing the 2016 target due to a change in the cabinet leaders, the work and definition produced over their 8 working years is still endorsed by the industry and the government. Furthermore, no other organisation has been set up to carry on with this work and many elements of the definition have been directly incorporated into current building regulations. For instance, many of the energy efficiency targets have been incorporated into Part L of the building regulations [ZCH, 2016].

The UK government has also released a specific numerical target for the annual PEC which is 44 kWh/m^2 [BPIE, 2015]. It is confirmed that this is an intermediate target and that currently the government is focussing on incrementally increasing energy performance requirements before publishing an official definition nearer to the 2020 deadline.

Looking at other available definitions:

One the most widely-used definition of nZEBs is developed by the 'National Renewable Energy Laboratory' (NREL). This definition places emphasis on the use of on-site renewables and makes it a requirement that the building needs to generate an equal amount of energy as it uses on an annual basis. It also considers costs and carbon emissions. This is very similar to the definition developed by the International Energy Agency (IEA), although the IEA considers nZEBs as dwellings which do not rely on any fossil fuels [Voss and Riley, 2009]. The United States Department of Energy (DOE) has also released a definition which applies to both residential and commercial buildings. The main consideration in this definition is that the nearly-zero balance should be met via renewables, similarly to the EU definition [DOE, 2008]. The California Energy Commission (CEC) has described a nZEB as a building which would meet its energy efficiency target via renewables and would be grid connected [CEC, 2009].

Overall, the variations in currently available definitions are minute. Most importantly they all cover the same areas of focus as they consider the use of renewable energy, the zero-carbon balance, grid connections, and the costs.

Table 2. 2: Building fabric, primary energy consumption and carbon emissions of the residential nZEB target

	Residential nZEB Target
Wall (W/m^2K)	0.11
Floor (W/m^2K)	0.10
Roof (W/m^2K)	0.80
Windows (W/m^2K)	0.13
Air permeability rate ($m^3/h/m^2$ @50Pa)	1.0-3.0
Primary Energy Consumption (kWh/m^2)	44
Carbon Emissions ($Kg/CO_2/m^2$)	10

2.4. nZEB Design Methodologies And Practices

After looking at specific case studies and exploring the different design measures incorporated to make them nZEBs; it is now essential to analyse the current paradigms in design practices of nZEBs. As can be seen from the previous examples there are many ways to achieve nZEB standards. The two main (basic) ways are as follows:

- 'Design as usual:' in this design route, the designer designs the building envelope and selects equipment in a traditional way, which does not take into consideration energy efficiency and such. Once this is done, several measures can then be implemented to offset the energy needs, thereby reaching the nearly zero energy balance. The disadvantage of this method is that it can involve the need of large size systems for the generation of energy from renewables. This can get very expensive [Yangang et al. 2011; Hootman, 2012; Kalema et al. 2008].
- 'Design as a nZEB:' on the other hand, one can design a very energy efficient building envelope and select energy efficient equipment. In this case the size of the systems required can be greatly reduced, thereby, reducing costs [Hootman, 2012; Kolokotsa et al. 2010].

In both cases achieving an optimum trade-off point, whereby, investment in generation systems meets the demand; is dependent upon the local climatic condition. The UK can be considered a 'cold dominant' climate, therefore, buildings would require constant heating to achieve comfortable indoor environments [Kolokotsa et al. 2010]. Thus, investing in triple glazing will be very cost effective in the UK in comparison to investing this in a 'heat dominant' climate country such as Mexico.

The above discussion focuses briefly on design practices for new buildings. However, it is essential to recognise that the approach for retrofitting an existing building to achieve nZEB standards presents some particularities. These arise from the loss of autonomy with regards to design features, such as elements of the building envelope, building façade, and solar orientation

[Yangang et al. 2011; Attia, 2012; Salem et al. 2019b]. Furthermore, for a new building the payback of the incorporated measures is the difference in cost between the standard available option and the energy efficient one. On the other hand, the retrofit of building components (envelope or equipment) that are still functional, means, the new measure will need to produce a payback for the cost of the entire alternative measure and not only the cost difference between 'standard and alternative' [Yangang et al. 2011; Kolokotsa et al. 2010; Salem et al. 2020a]. Nevertheless, this is still dependant on the residual life-time expectancy of those existing building components [Kolokotsa et al. 2010]. For instance, if an existing component needs to be replaced regardless of whether the building is undergoing retrofitting or not then this would mean the payback is more easily attained. A NREL study highlighted the difficulty of dealing with retrofitting as it monitored six buildings across the U.S. to investigate whether they can be retrofitted to achieve nZEB standards. The study concluded that a single storey office building could achieve NZE performance, however, a two-storey building could not (Torcellini et al. 2004). These additional boundaries regarding retrofitting means the optimum trade-off point also differs in comparison to new buildings. For a retrofitted building one can expect the trade-off point to be reached at a higher level of demand and therefore a higher level of generation compared to new buildings [Figueiredo, 2010; Yangang et al. 2011].

Energy consuming activities within a hotel can be split into two main categories one of which would be any activities that involves the guests and their comfort: for example, guests' rooms, reception, bar, and restaurant. Meanwhile other activities that do not directly involve the guests include kitchen, laundry etc. Interestingly, it has been reported that activities that do not directly involve guests are typically the largest contributors to the total energy consumption of the hotel. This suggests that a focus on reducing the energy demand of such activities through the incorporation of relevant energy efficient measure (EEMs) would lower the overall energy demand and increase the energy efficiency of the hotel building.

2.4.1. Retrofit Interventions

The analysis of various nZEB case studies and conclusions confirmed that to successfully retrofit an existing building into a nZEB then the following factors or building elements need to be considered.

A study by Ardente et al. [2011] suggested that improving envelope thermal insulation, glazing and lighting contributed to significant energy consumption reductions. First, because building fabric of most existing buildings is outdated and performs poorly, improvement of fabric insulation levels is necessary [Ma and Wang, 2012; Attia, 2012]. According to a study by Paoletti et al. [2017] Expanded polystyrene (EPS) is the most common material used in walls for both residential and commercial buildings across Europe (30% of buildings). Meanwhile, stone wall is most used in roofs (22% of buildings). The study concluded that the choice of insulation material for both cold and warm climates seems to be "homogenous." In other words, climatic condition does not affect the type of insulation material adopted. Basarir et al. [2016] found that an energy efficient retrofit of a school building envelope approximately reduces one-third of the current annual fuel cost. The notion is corroborated by Osama et al. [2015] where they concluded that envelope retrofit can reduce energy consumption by up to 28%.

Improved glazing is a well-recognised way to significantly improve the overall energy efficiency of the building fabric. Without adequate glazing, even an energy efficient heating system, will not work or run economically [Paressa et al. 2015; François et al. 2017]. This is because heat transmittance through windows is five times larger than other components of the building envelope [Ihm et al. 2012, Chan et al. 2009, Sudhakar et al. 2019]. In hotter conditions solar heat gain can contribute to increased cooling demand. Glazing therefore has a significant effect on the heating and cooling demand of the building. Although double glazing usage has increased in recent years, many buildings still use single glazing with poorly insulated frames. Single glazing has a U-value of 4.5-5.6 W/m^2K. This is not compliant with current building regulation standards not just the nZEB standard. Generally, buildings in hotter countries require glazing that will reduce solar heat gain and enable cooling. Meanwhile, the opposite is true for buildings located in colder climates [Chan et al. 2009, Capozzoli et al. 2013, Sudhakar et al. 2019]

Lighting is the third largest contributor to emissions for UK homes. It accounts for 20-50 percent of a typical building's electricity demands and therefore if tackled and made efficient, it can have a very positive contribution to lowering consumption and overall emissions [Figueiredo and Martins 2010; EST, 2019]. Selecting lighting that has high efficacy (at least 50lm/W) contributes to lower energy consumption [Steffy 2002]. Lighting has an impact on occupant comfort. Low lighting, glare, and flicker can contribute to discomfort, headache trigger, and eyestrain. It is, therefore, vital that good quality lighting is in place. Studies have shown that good quality lighting can increase productivity and reduce error [Figueiredo and Martins 2010; Carbon Trust, 2013]. In comparison to incandescent and fluorescent lighting, LED lighting has the highest efficacy, light output, and lamp life; they can provide energy savings of up to 80%. LEDs can also be used in a vast majority of settings and applications. When combined with automatic controls they have been proven to provide cost savings of 30-50%.

Improvement of the building fabric also refers to improved air tightness that contributes to minimal air leakage. Normal air movement in and out of buildings is known as air leakage. Air leakage is measured by air change per hour (AC/H). Natural weather conditions, such as temperature differences and wind can increase air leakage. Airtight constructions mean adequate ventilation is necessary to maintain high level of indoor air quality and prevent air leakage and overheating. With very high airtightness levels, mechanical ventilation (MV) becomes a requirement [Michael and Chris, 2009; EST, 2019]. MV ensures that air exchange within the building is achieved at a certain rate. Analysis of the nZEB database, Zebra2020 project, shows that 89% of nZEB buildings across Europe have mechanical ventilation (84% with heat recovery). MV with heat recovery systems reduce heating and cooling demands by replacing the outgoing air with pre-heated/cooled incoming fresh air. In addition to improving occupant comfort, MV systems reduce moisture, indoor CO_2 concentration and potential air contaminants.

Winter heating and domestic hot water (DHW) is a particularly important consideration for UK homes due to the UK's cold dominant climate. Heating homes in the UK contributes to approximately 40% of emissions and is the main source of energy consumption within homes. [Jokisalo and Kurnitski 2005; Paressa et al. 2015, EST, 2019]. Utilising the Zebra2020 project, it is found that 60% of existing nZEB buildings use a single system for both heating and DHW needs. A heat pump is the most used system followed by boiler systems (23%). Solar thermal systems made up 1% of used technologies within nZEBs across Europe. Interestingly, 42% of heat pumps were used in warm-mild climates. This is largely because the system can achieve a high level of performance with mild external temperature. Furthermore, it can be used to also meet cooling needs during the summer. Renewable systems are a vital part of achieving nZEBs as it is a requirement that energy generation within buildings should come mainly from renewables [Kolokotsa et al. 2010; François et al. 2017].

A projected increase in energy demand combined with a growing energy supply gap means that energy generation must be optimised. Traditionally, energy consumption loads are supplied by electricity from the national grid and/or heat generated via fuel burning in a boiler. This conventional approach to generating energy 'separately' tends to have a low efficiency of 30-45% [ACEEE, 2018]. Consequently, in recent years there has been an increasing interest in the incorporation of Distributed Energy Resource (DER) systems, ranging from renewables to co/tri-generation systems, in residential and commercial buildings. Combined Heat and Power (CHP) or cogeneration is an alternative method that utilises, by-product heat, which can amount up to 80% of total primary energy during electricity generation [ACEE, 2018]. Studies have shown CHP can improve efficiency by over 30% and deliver primary energy savings of more than 50% when compared to conventional generation [DFIC, 2016; Jing et al. 2012]. Combined Cooling, Heating and Power (CCHP) also known as tri-generation originated from CHP. The difference between the two systems is that CCHP further utilises by-product heat to provide cooling [Medved, 2011].

CHP benefits from more than 100 years of experience in both commercial and residential applications and is usually described as the generation of electricity and thermal energy using one primary energy source. Since the introduction of the 2004 EC Directive on the promotion of cogeneration [Directive 2004/8/EC] the UK government has actively supported and promoted the development of cogeneration in the UK, given the potential benefits with regards to the reduction of primary energy and emissions, by introducing the initiative 'CHP Focus.' The initiative aims to inform, guide, and aid residential and commercial users regarding CHP as a technology and approaches to financing a CHP plant [DECC, 2017]. Consequently, between 2007 and 2016 the UK has seen an increase in the installation of CHP units by 48.97% [DUKES, 2017].

The development of CCHP technology and on-site application gained popularity in the last two decades and have been widely introduced in research into commercial building applications such as hospitals, office buildings, and hotels [Arcuri, Florio, and Fragiacomo, 2010; Smith, Mago, and Fumo, 2013]. Air conditioning and cooling systems are standard in many commercial buildings, even in countries with a cooler climate such as the UK [CIBSE, 2016]. A CCHP unit will allow the utilisation of excess heat for cooling by creating water at sufficiently low temperatures to be used for air conditioning [Medved, 2011]. Due to this, the overall efficiency of a CCHP unit is significantly higher in comparison to the CHP plant and tri-generation systems can reach overall efficiencies up to 93% [Desideri, Manfrida, and Sciubba, 2012].

Below is a summary of the impact of some of the most used renewable energy solutions.

Table 2. 3: Summary of the noted impact across the literature of various renewable/microgeneration systems

System type	Results	Reference
Photovoltaics/Solar thermal	photovoltaic and solar thermal systems are the most common technologies used across Europe. Their contribution reduces the total primary energy demand. Furthermore, solar panel systems can contribute to cost savings of £335 a year	Zangheri et al. 2017; EST, 2019
Ground source heat pump	Closed loop GSHP can reduce energy use and air pollution emissions-up to 44% compared to air source heat pumps and up to 72% compared to electric resistance heating with standard air-conditioning equipment	Morck et al. [2013], GHS 2015
Wind power	The biggest wind turbines generate enough electricity in a year (about 12 megawatt-hours) to supply about 600 homes. From 2000 to 2015, cumulative wind capacity around the world increased from 17,000 megawatts to more than 430,000 megawatts. In 2015, China surpassed the EU in the number of installed wind turbines and continues to lead installation efforts.	Zangheri et al. 2017; NG, 2019
Biomass Boiler	If it is replacing an older LPG heating system with a wood-burning system savings can amount up to £1,205 a year, but if it is replacing an old electric heating system the savings are around £960 per year. However, if a new (and more efficient) system is in place, such as a modern condensing gas or oil boiler, a biomass boiler is likely to cost more to run than those systems.	Zangheri et al. 2017; EST, 2019

2.5. Life Cycle Cost Analysis

A life-cycle cost analysis (LCCA) is an established methodology that allows the evaluation of a certain project and in which all costs accrued from the life stages of a building are considered. Those life stages include investment, operation, maintenance, and replacement costs. A LCCA provides considerably better evaluation of the long-term cost-effectiveness of refurbishment investment in comparison to different methodologies that only focus on initial costs, or just the payback period of the investment. Furthermore, a LCCA helps investors to assess and decide which refurbishment strategies are financially suitable for their budget. This section provides an overview and analysis of the literature studies that have used this method to evaluate nZEB retrofits and their outcomes and recommendations to help guide this research and answer the research questions.

2.5.1. Residential nZEBs

Several studies have demonstrated that reaching the nZEB standard for residential buildings is technically feasible [Kurnitski at al. 2011; Hamdy et al. 2013; Pikas et al. 2014]. Meanwhile, reaching the nZEB standard whist considering costs and cost-optimality of the retrofit process and of the individual EEMs remains challenging. Consequently, although there are many studies that focus on the retrofit of buildings to reach the nZEB standard, fewer consider cost-optimality and reaching a cost-optimal solution. Moreover, many of the definitions that have been or are currently being released throughout the EU only consider energy efficiency, once again neglecting cost-efficiency of the retrofit process. Nair et al. [2010] for instance highlighted that cost can be one of the most significant factors in influencing the energy efficiency investment for existing residential buildings.

Hamdy et al. [2013] presented a multi-stage simulation-based optimisation method to find cost-optimal and nZEB solutions for a single-family house located in Finland. The results demonstrated that a nZEB with a PEC of 70 kWh/m^2/yr is economically feasible and a range of ≥93 and ≤ 103 kWh/m^2/yr is a cost-optimal energy performance level. Furthermore, the sensitivity analysis showed that an optimal implementation of energy retrofit solutions depends on the installed heating/cooling system and the escalation rate of the energy price. A different study identified the cost-optimal range for nZEBs as 140 $kWh/m^2/yr$ and 0.33 W/Km^2 envelope insulation level, including transmission and infiltration losses per unit heated floor area [Kurnitski at al. 2011]. Comparison of various wall, floor, roof insulation levels and two types of windows and mechanical ventilation with heat recovery systems for a reference residential house showed that a reduction of 23-49% in the space heating energy is the optimal range for retrofitting the house.

Despite perceived long payback periods and high initial capital investment costs it was demonstrated that triple glazed argon filled windows with a small window to wall ratio, and 200 mm thick insulation on the wall with a payback period of 20 years present a cost-optimal solution for an office retrofit [Pikas et al. 2014]. This highlights the importance of carrying out a LCCA to identify which retrofit solutions and EEMs are truly cost-optimal rather than purely rely on the capital investment costs as an indicator of cost-effectiveness. A study conducted in Portugal in the suburbs of Porto on a multifamily building determined that retrofitting to the nZEB standard can be achieved with a payback period of 13.5-15.0 years [Silva et al. 2018]. Rodrigues et al. [2014] concluded that the nZEB standard could be achieved for a 19th century masonry building with an 11 year-payback period.

Kapsalaki et al. [2012] investigated the design of cost-efficient nZEBs in various climates. It was found that the differences between a cost-efficient and inefficient nZEB can be more than three times in terms of initial and total LCCs. Neroutsou and Coxford [2016] investigated whether a deep retrofit of buildings is a better approach in comparison to a retrofit strategy with lower capital costs on an existing Victorian house in London. It was concluded that rising gas prices, low discount rates, and a long study period made the extensive retrofit an efficient option.

Plysly and Kalema [2015] evaluated four building tightness levels, three ventilation-heat recovery types, and nine heating systems to select a cost-effective low-energy solution for a residential house. It was found that improving the thermal insulation of the building is the most preferable retrofit solution to lowering the dwelling's heat energy demand. On the other hand, a comparative analysis for the selection of an alternative residential energy supply system found that a micro-CHP is a practical and cost-effective alternative in comparison to traditional heating systems [Alanne et al. 2007].

2.5.2. Commercial nZEBs

As this thesis only explores Hotels for the commercial sector, this section primarily focusses on this.

Many studies have assessed the energy consumption of the hotel industry and have often concluded that hotels are typically energy intensive buildings [HES 2011; neZEH 2017]. Lowering the energy consumption in hotels through the implementation of individual EEMs or a whole building retrofit can offer not only environmental benefits but also financial ones. This is corroborated in the findings of the 'nearly zero energy hotel' (neZEH) project which highlighted that the hotel industry in general acknowledged the financial benefits of retrofitting not only as a result of reduced operational and maintenance costs but also due to increased competitiveness as a result of improved image [neZEH, 2019]. This is in consonance with many other studies [Bohdanowicz 2005; Le et al. 2006; Lu et al. 2012; Radwan, Jones and Minoli 2012; Pirani and Arafat 2014].

There is evidence that commercial nZEB retrofit projects make up a smaller percentage of overall nZEB retrofits. One paper identified four main reasons why retrofits may not be taken up as much for commercial buildings. Three of the reasons are due to financial aspects of the retrofit, namely, stakeholders may only look at short-term profitability, there is inconsistent data about profitability and budgetary constraints [Juhani and Jaako, 2012]. This highlights the importance of selecting retrofit solutions that are economically viable. Most importantly, that this can also be demonstrated to stakeholders

Substantial research effort has been undertaken to investigate the importance of improving the energy performance of hotels. Yet, there is a lack of available literature on commercial nZEB hotel retrofit. Ferrara et al. [2018] conducted a literature review on nZEB building refurbishment cost studies and found that the most studied building type is residential buildings (68%); within commercial buildings, 18% were office buildings, 5% were retail, and only 4% were schools. There is a need for further studies of cost-optimal nZEB refurbishment. Table 2.4 is included to explore hotel retrofits in general and the factors that encourage/discourage hoteliers' and guests decision when it comes to retrofitting and staying in a 'green hotel,' respectively. From Table 2.4, it is learnt that both guests and hoteliers appreciate the importance of an environmentally friendly hotel. However, further encouragement is required to ensure that hoteliers are fully aware of the financial benefits of improving the energy efficiency of their building. In addition, official incentive schemes should be introduced to also encourage and assist hoteliers in making the transition towards an energy efficient hotel.

A study examined the technical and economic aspects of various retrofit measures on a typical 4-star hotel located in the South of Portugal (Faro). They concluded that the cost-optimal solutions include control of equipment, systems, improving water use efficiency, efficient lighting, and total re-design of the ventilation system [Corradoa et al. 2016]. Using two Italian reference buildings it was [Martinopulos, 2018] found that a heat pump combined with a PV system seemed to be the most cost-effective solution to meeting the nZEB Italian standard requirements. Several studies found that installing renewable energy systems to substitute traditional fossil fuels had competitive economic payback periods [Asbdrubali et al. 2019, Simons and Firth, 2011, Zangheri et al. 2017]. A similar study looked at investigating the performance gap between cost-optimal and nZEB retrofit options for an Italian reference hotel and concluded that the nZEB standard had a global cost at least 50% higher than the cost-optimal solution. It was also noted that retrofit packages with better economic performances exhibited poorer comfort levels [Marszal et al. 2011].

One paper investigated reaching the nZEB standard on several reference buildings from various countries [Norcera et al. 2019]. It was found that there appears to be a pattern between the nZEB building regardless of location. For example, the nZEB building typically has high levels of insulation, double or triple glazing (depending on local climate), an efficient boiler or ground source heat pump (GSHP) and a renewable solar system. However, whilst it was noted that the nZEB retrofit did not vary significantly, the same could not be said for the cost-optimal benchmark. Furthermore, it was difficult to reduce global costs (energy, investment, replacement, and maintenance costs) whilst ensuring the standard is fully met. Furthermore, it was highlighted that one of the most significant barriers to obtain a valid and reliable cost analysis is the collection of reliable data for the renovation costs

Using an Italian reference hotel Buso et al. [2017] investigated whether there is a match between the cost-optimal solution and the nZEB solution. It is found that the financial analysis presented a 'worrying gap' between financially optimal solutions and the nZEB ones. This is unsurprising as various studies investigating the currently available nZEB definitions concluded that many of the national plans being released and implemented have "missing or vague information" [Marszal et al. 2011; Satori et al. 2012; D'Agostino 2015; D'Agostino et al. 2016; Salem et al. 2019a]. In general, the energy consumption between hotels varies depending on the size, quality and type of service, and occupancy rates. Tournaki et al. [2014] suggested some reference levels for nZEB hotels: 77-134 kWh/m2/yr for new builds and 93-175 kWh/m2/yr for existing builds (depending on the climatic zones).

Niemela et al. [2016] determined that a nearly zero-energy building (nZEB) target can be cost-effectively achieved in renovations and that modern renewable energy production technologies are cost-efficient and should be recommended. Carter and Keeler [2008] demonstrated that green roofs increase total net present value costs by 10–14%, and construction costs need to decrease by about 20% before green roofs become cost-effective in comparison to conventional roof designs.

Journal	**Author(s)**	**Findings**
1) Energy Conversion and Management 2) Entropy	1) Nocera et al. 2019	❖ One-star hotel managers/owners are less likely to be willing to invest in renewable energy and energy efficient retrofit of their buildings in comparison to 2-5-star hotels
Cornell Hospitality Quarterly	1) Butler 2008 2) Dolnicar, Crouch, and Long 2008	❖ Green hotels have better performance in terms of thermal comfort, acoustics, lighting, and indoor air quality [1] ❖ Although financial benefits can be gained from the overall reduction in energy consumption associated with green hotels, hoteliers are reluctant to implement measures that may lead to the discomfort of guests [2]
1) Renewable Energy 2) International Journal of Hospitality Management	1) Kostakis and Sardianou 2012 2) Chen and Tung 2014	❖ Guests are willing to pay more for environmentally friendly hotels [1,2] ❖ Guests do not mind minor discomfort (e.g. reusing towels, using recycled products) if it means helping the hotel remain green and helping the environment [2] ❖ Factors that affect whether guests are more willing to pay for a green hotel are gender, age, and level of environment consciousness and awareness [1, 2]
International conference GREDIT	1) Cingoski and Petrevska 2018	❖ Contemporary guests “expect” hotels to be environmentally responsible ❖ The case-study (a 5-star) hotel was willing to become an eco-hotel due to the perceived benefits of lowering operational costs and energy consumption

Table 2. 4: Summary of literature review		❖ It was recommended that the introduction of subsidies will encourage more hoteliers to run a high energy efficient hotel
Annals of tourism Research	1) Le et al. 2006	❖ Social/government pressure to retrofit has a weak influence on hoteliers' decision to retrofit, unlike perceived competition and customer demand. ❖ Building characteristics such as the size and location of the building had a weak influence on decision to retrofit.

2.6. Building Modelling and Simulation

Currently building modelling is an essential part of building design. This is because of the increase in standards of buildings regulations [CIBSE, 2015]. Building modelling and simulation tools are used to evaluate regulatory compliance by predicting energy performance, produced and mitigated CO_2 emissions, overheating analysis, and the building's interaction with its external and internal environments [Spitz et al. 2012; Hygh et al. 2012].

The quality of input data used to complete a thermal model has a significant effect on the accuracy of the energy simulation model produced and the outputs [Calleja Rodríguez et al. 2013; Babaei et al. 2015]. However, factors such as occupancy behaviour (as mentioned previously), plug load consumption, and weather data cannot be entirely reproduced to match real-life conditions. This is especially true for new buildings in the design stage that have not been occupied yet. Furthermore, factors such as over-simplified modelling assumptions, poor energy management, and poor maintenance of building systems and components can affect the outcome of the energy performance of the building [Demanuele et al. 2010]. This is where the importance of conducting a thorough and accurate site survey (especially for existing buildings) plays a significant role. By spending time collecting all the necessary input data and information required the number of modelling assumptions are reduced and the model created can therefore be a replica of the actual building.

Building modelling and simulation software Tas is used throughout this thesis to predict energy performance, usual and mitigated CO_2 emissions, proliferate thermal and therefore occupant comfort [Edsl, 2020]. Tas is used as it can offer complex computational dynamic fluid simulation and it has been fully accredited for UK building regulations 2013, BS EN ISO standards, and has Cibse accreditation. Other thermal analysis simulation software such as integrated environmental solutions (IES) and Design Builder are available and offer the same capabilities. However, Tas excels other available software due to the ability to dynamically model individual plant components to reflect the actual building's components. Meaning that each system can be edited as required to match the real-life setup of all building components. Furthermore, even complex systems that are not in the existing Tas database can be created and modelled step by step. These can then be added to the library for use on any future projects that may use the same system.

Tas allows the copying of final outputs to other programs such as Excel and IBM SPSS for analysis due to its text-based results option (in addition to the standard graphic user interface). Final output reports can be created in PDF format or as an Excel spreadsheet. The system also allows the user to "extract the desired results over the time period of interest, whether this be annual, monthly, daily or hourly in an easily interpreted and accessible format" [Edsl, 2020].

2.6.1. The Performance Gap

Studies have shown that the assumptions used to create dynamic thermal models of buildings do not reflect their actual energy use [Gram-Hanssen 2010; Raslan and Davies 2012; Hamilton et al. 2013; Rotimi et al. 2017]. This is known as the performance gap. Generally, it has been found that the energy performance of the actual building is higher than the energy performance of the modelled building, even when the modelled building is essentially a replica of the actual building.

Although having regulations that stipulate designing or retrofitting buildings to be nZE can provide occupants with comfortable living conditions that are not energy intensive, it does not influence plug load consumption. Furthermore, it has been argued throughout literature that one of the most significant factors that affect the energy consumption of a dwelling is the occupant behaviour [Gram-Hanssen 2010; Raslan and Davies 2012; Hamilton et al. 2013; Truong and Garvie 2017; Rotimi et al. 2017]

For UK residential dwellings there is a lack of investigation into the performance gap associated with simulation studies. As discussed earlier the energy performance gap can be explained as a difference between actual and modelled, or predicted, or theoretical energy consumption. A large scale-study investigated the energy performance gap of around 200,000 dwellings in the Netherlands [Majcen, Itard and Visscher 2013]. It is found that energy-efficient dwellings in general consume more energy than initially predicted. It is highlighted that whilst simulation studies or theoretical calculations can meet the energy target reductions required by policies and targets, in real life the actual energy reduction potential of dwellings "fails to meet most of the current energy reduction targets." This is in consonance with several other studies that have reported that the energy consumption of actual dwellings is typically higher than the modelled or calculated one [Bordass, Leaman and Ruyssevelt 2001; Branco, Lachal, Gallinelli and Weber 2004; Guerra-Santin and Itard 2010; Cayre et al. 2011; Raslan and Davies 2012; Bouchlaghem, and Buswell 2012; Hamilton et al. 2013].

Throughout the literature simulation studies have proven consistently that reaching high energy performance standards such as the nZEB standard and the Passivhaus standard is technically feasible [Dan et al. 2016; Truong and Garvie 2017]. However, whether this transfers to real-life applications has been mostly unexplored and no consideration has been given to occupants and their interactions with such energy efficient buildings. A recent paper by Hargreaves, Wilson, and Hauxwell-Baldwin [2017] investigated ten households that incorporated a range of smart technologies to reduce energy consumption and optimise energy management over nine-month. It is concluded that there is a risk that such technologies may increase energy usage and in general they generated little energy savings.

The concept of an energy efficient or a smart home leading to an increase in energy usage by occupants has been investigated previously in the literature and has been labelled as the 'rebound effect.' Herring and Sorrell [2009] defined the rebound effect as the increase of energy consumption following renovation to improve the energy efficiency and reduce energy costs due to occupant behaviour.

Some researchers have claimed that the energy performance gap can be mainly explained by occupant behaviour [Aydin, Kok and Brounen 2013; Gram-Hanssen 2011]. Yet, there continues to be a lack of widely available occupant data to fully confirm the influence of occupant behaviour on energy consumption. This is because most studies that investigated this have used pre-occupancy data as opposed to post-occupancy data due to the time-consuming and intrusive nature of carrying out such monitoring. However, to improve simulation models and set realistic energy targets and recommendations it is vital that actual occupant behaviour is investigated and understood. Studies that did not explore pre- or post-occupant behaviour have focussed on occupant characteristics instead. Two different studies in England have confirmed that there is a positive correlation between household income and actual energy consumption [Druckman & Jackson, 2008; Steemers and Yun 2009].

The specific ways in which occupant behaviour can potentially influence energy consumption include number of heating hours, set-point temperature, how frequently hot water, lighting, and appliances are being used. Santin [2011] found that even using a radiator for different number of hours in different rooms around a dwelling can lead to a variation in the actual energy consumption. For example, the variance for the living room is 8.8% and for the bathroom it is 5.9%. Gerdes, Marbus and Boelhouwer [2014] discussed how the number of people per household has a significant influence on the energy used for DHW. Meanwhile, a larger number of household occupants leads to a decrease in the energy consumption per person (but overall higher energy consumption) [Chen, Wang and Steemers 2013]. As time and technology change studies have recorded a change in the mix of energy use within households. For example, energy use for cooking has continually decreased over the past few years, however, energy use from electrical appliances has increased significantly [Gerdes, Marbus, & Boelhouwer, 2012; Gerdes et al. 2014; Gerdes, Marbus and Boelhouwer 2014].

2.6.2. The Influence of a Changing Climate On Building Performance

Fluctuations in climatic conditions can influence a building's energy performance. Most importantly, there is a direct effect on thermal comfort of occupants where extreme changes in weather conditions occur. It has been predicted that within the UK there will be a shift from high heating and little/no cooling demand to a substantial increase in cooling demand during summer. Such projections therefore necessitate a shift in the way buildings are currently being designed and retrofitted.

Crawley [2008] highlighted several years ago that the influence of a changing climate on buildings and their components have been mostly ignored. Furthermore, William et al. 2011 corroborated that currently buildings are typically designed without taking into consideration how changes in future climatic conditions will affect the performance of buildings.

A London study investigated the impact of climate change on the design and performance of buildings. It is found that the temperature and solar radiation has significantly changed in the last 15 years [Oreszczyn, 2012]. Frank [2005] examined the impact of climate change on the heating and cooling demand of buildings. The results highlighted that depending on the weather projection used the heating demand could potentially decrease between 44% and 81%. Similarly, Berger et al. [2014] explored how the energy consumption for nine office buildings would be affected by future climate change and concluded that the heating demand could decrease between 11% and 30%. It is noted that the age of the building seemed to influence those percentages.

The above signifies that buildings can be particularly vulnerable to changes in climatic conditions. Adapting existing buildings and designing new buildings whilst taking into consideration the influence of a changing climate therefore becomes vital.

2.6.3. CIBSE Test Reference Years (TRYs) and Design Summer Years (DSYs)

The Chartered Institute of Building Services Engineer's (Cibse) weather files are typically utilised within the UK's construction industry for simulating and examining thermal comfort of buildings [Connick, 2015]. Two types of weather files are provided by Cibse, known as the 'Test Reference Year' (TRY) and the 'Design Summer Year' (DSY). Using 14 different locations around the UK, between 1983-2005 and currently 1984-2013, Cibse gathered 20 years of real weather data including data regarding : dry bulb temperature (°C); wet bulb temperature (°C); atmospheric pressure (hPa); global solar irradiation (W·h/m2); diffuse solar irradiation (W·h/m2); cloud cover (oktas); wind speed (knots); wind direction (degrees clockwise from North).

The Test Reference Years (TRY) weather files are comprised of hourly data over a typical year. They are used to establish the average energy consumption within buildings using simulation software. In other words, they are suitable for energy analysis. The data within the files has been selected from 20-year data sets. Initially the TRY files used a baseline of 1984-2005. However, this has now been updated and currently the files are based on an updated baseline of 1984-2013.

The Design Summer Years (DSY) weather files are comprised of a continuous yearly sequence of hourly data, from the 20-year data sets which have now also been updated to use a baseline of 1984-2013. They represent a year with a warmer summer. They are therefore suitable for assessing the risk of overheating within buildings. The recent probabilistic DSY files have been improved so that they offer a better representation of overheating events, their relative severity, and expected frequency. The probabilistic DSY defines three types of overheating events:

1. DSY 1: features a moderately warm summer year
2. DSY 2: features a moderately warm summer with short intense high temperatures
3. DSY 3: features a long, intense warm spells.

Based on the research questions being explored for each case study, the selection of the weather file will vary. In addition, based on the location of the case study. Crawley [1998] highlighted "no single year can represent the typical long-term weather patterns. More comprehensive methods that attempt to produce a synthetic year to represent the temperature, solar radiation, and other variables within the period of record are more appropriate and will result in predicted energy consumption and energy costs that are closer to the long-term average." It is generally recommended that where possible the weather file selected should be in close proximity to the location of the case study being examined [Cibse, 2018]. Tas and other simulation software also recommend that the existing preselected 'typical years' weather files that are within 20-30miles (30-50km) of the case study will most closely match the long-term climatic temperature, solar radiation, and other relevant variables.

2.6.4. Chapter Summary

This chapter presented detailed review and analysis of the current state of the surrounding concept of nZEBs. Based on the findings two definitions are aggregated for UK residential and commercial nZEBs. Furthermore, the chapter offered a detailed review and analysis of the latest theoretical contributions and analysis of various nZEB residential and commercial case studies (reference and actual case studies). The currently available methodologies to reaching the nZEB standard are presented and evaluated. The risks surrounding achieving the nZEB standard are also discussed and analysed. This chapter forms the foundation for guiding this thesis. The identified gaps in knowledge, the design methodologies identified, the risks and mitigating strategies are all utilised to shape the methodology, investigations, results, and analyses explored in the following chapters.

CHAPTER 3: METHODOLOGY

3. Chapter Introduction

This chapter introduces the research paradigm and design to be followed for addressing the research questions of this thesis. The computational modelling software to be used is introduced. The LCCA methodology is also presented. Finally, the CIBSE TM59 Overheating Criteria is introduced and explored. All those different methodologies are explained in detail and step-by-step throughout this chapter.

3.1. Research Paradigm

Within research, a paradigm may be considered a guiding principle which influences the researcher to raise specific and relevant questions and use a suitable research approach to systematically address the research questions, in essence – a methodology. It is well-known that certain paradigms correspond to specific methodologies. For instance, an interpretative paradigm usually utilises a methodology that is qualitative [Claire et al. 2012]. Although it must be noted that this is not invariable, as it is up to the researcher to select the paradigm and its associated methodology, as they see apt, depending on the research questions, paradigmatic standpoints and predilections of the researcher.

Not uncommon to computational studies, this research project will follow the 'Positivist' research tradition as this fulfils the requirement of an analytical, pragmatic, and empirical inference. This approach favours data collection and interpretation in an objective way. Furthermore, the research findings are observable and quantifiable [Collins 2010]. Factual information gathering is an essential part of the positivist approach, for example for this study this will include the real site data that is collected and validated against the modelled data by comparing the energy consumption. With these assumptions, the goal is usually a generalised framework that can be altered based on new findings [Sondhi 2011]. Once again this is in line with the ultimate objectives of this thesis, which include creating several frameworks that act as a guide regarding how the nZEB standard may be achieved and the developed framework should be updated as further research is conducted and as new technologies emerge.

Lehman [2004] defines epistemology as the abstraction of the fundamental metaphysical or ontological assumptions of a discipline into theories of knowledge acquisition. Epistemology is about questioning the current knowledge and its components and questioning the need and resultant endorsement of those fundamental aspects. Essentially, epistemology structures a paradigm, in the case of this work, Positivism, into a functional form, so that one may develop theories from observations which are then formulated, substantiated, and finally accepted or rejected.

The methodology addresses the research questions. The identified research questions within this thesis can all be effectively addressed using a quantitative methodology. The data collected and used throughout the work is numerical data. This numerical data is analysed for trends and relationships thereby ensuring that appropriate and verifiable conclusions are drawn. In general, a quantitative research has the advantage of 'scientific detachment,' whereby the researcher's findings and interpretations are objective as they are supported by empirical evidence [Burke and Larry, 2010]. This approach is therefore consistent with the epistemological notion of quantitative research where there is an impartiality between the researcher and the examined phenomena.

3.2. Research Design

A suitable research design must take into consideration the principal theoretical and philosophical aspects and assumptions of the research [see section 3.3.2] to be successfully applied, shape the knowledge gained from the literature review, and produce constructive results (Creswell, 2014). It is the first step in establishing and developing the research and it is what enables the researcher to obtain the most accurate and representative results possible.

The research design of this work is based on the study of reaching the nZE standard in both residential and commercial UK buildings and assessing the performance of said buildings on current and future climate projections by conducting a comprehensive investigation of the impact and reciprocity in terms of energy reduction and cost efficiency of various design solutions.

Initially it is vital that previous case studies of residential and commercial buildings are explored and analysed to establish the current paradigms in design practices of nZEBs. This is because understanding the energy performance of previous and current case studies is an important and significant step towards achieving a nZEB, considering the limited availability of national and international definitions available. This was explored throughout the literature review.

Building modelling and simulation software Tas is used to predict energy performance, usual and mitigated CO_2 emissions, proliferate thermal and therefore occupant comfort [Edsl, 2018]. The analysis of these various factors whilst taking into consideration the compound dynamic interaction between specific building elements of the model and the environment will verify the best routes and design variables that help in reaching the nZEB standard. To ensure validity and reliability of models created on Tas, the energy consumption results obtained from the simulation are compared to the actual consumption of the various buildings, where possible [see section 3.3.3].

3.3. Computational Modelling

3.3.1. Modelling Process

As discussed earlier, building modelling and simulation software Tas is used throughout this work to model and estimate the energy performance of buildings pre-and post-retrofit. Whilst Tas will be used for this work, it should be noted that other thermal analysis software is available. Examples of this include: 'SolidWorks,' 'Integrated Environmental Solutions' (IES), and 'Design Builder' [Designing Building Ltd, 2016]. Most thermal simulation software provides the same features. For instance, they all allow the use of CAD (.dwg) files which acts as an outline for drawing the walls and other building elements. Other features may include solar shading, incorporation of weather files for simulation (current hourly data and future projections), and prediction of the energy consumption and CO_2 emissions of the modelled building. Building modelling and simulation software are also typically used to check for regulatory compliance, overheating analysis, assess internal conditions such as ventilation, infiltration, and lightning gain.

Tas takes into consideration building geometry, construction, equipment, HVAC systems. To obtain a model that is a replica of the building being investigated, various structural input data and other parameters that impact the energy and thermal behaviour of a building are inputted as part of the simulation process. To be able to input all this data, first, an initial site visit is conducted to survey the actual building. This can be considered the first or preliminary phase of the simulation process. In this phase the site visit is conducted to collect AutoCAD plans, information regarding the actual building construction (year, material), systems, and plant details [this information can be found in each of the case study sections, under 'Building Description']. Furthermore, the actual monthly and annual energy consumption is collected for the latest year and the previous two years for comparison and validation [see section3.3.3].

The site data that is collected from the first phase is used to build a holistic baseline model on Tas. Firstly the AutoCAD drawings are used for obtaining measurements of doors, windows and floor height (as additional verification for the measurements taken during the site visit. Each floor is recreated on AutoCAD in a separate file with a 10m reference construction line and without any additional layers that may have been part of the original AutoCAD file. These drawings have the necessary zones, such as bedrooms, bathrooms, offices, kitchen, laundry etc., all categorised based on the usage of the space. This is an important step in the simulation preparation process as it directly affects the resultant internal conditions of the space once the building is simulated.

When populating the TBD file, such as filling out typical constructions of the building envelope, it is ensured that they represent the building's constructions, building fabric, glazing and year of construction. Once this is done the building's systems are specifically and individually designed within Tas systems utility to replicate the current HVAC systems/plants. Refer to figures 3.1-3.3 for a step by step explanation of the simulation process.

The EPBD suggests that the typical energy use in a building should consider heating, cooling, ventilation, lighting, and DHW. Within Tas, the total energy consumption considers heating, cooling, auxiliary, lighting, domestic hot water (DHW), equipment, and displaced electricity (where applicable). The carbon emission calculations take into consideration building systems, air/ plan side HVAC control(s), building envelope elements (insulation, glazing etc.), lighting/daylighting interaction(s), energy consumption, occupancy schedule, fuel type, ventilation, DHW etc. Finally, the PEC is the amount of primary energy consumed in order to meet the building's energy demand (heating, cooling, DHW, lighting, and auxiliaries) and is also the net of any electrical energy displaced, where applicable.

The retrofit phase of the methodology begins by utilising TasGenopt to select individual EEMs that are applicable to the case study and create the retrofit scenarios that meet the nZEB target. TasGenOpt is a utility within Tas software that performs parametric simulations. It minimises the number of simulations and time needed to achieve desirable design options (in this case the nZEB target values). GenOpt is currently the most utilised optimisation tool across the literature and was first utilised by Wetter and Wright [2004]. Karaguzel [2014] has demonstrated that GenOpt can be used to successfully reduce the LCCs of an office building by 28.7% over 25 years whilst reducing the energy consumption by 33.3%.

Similarly, Hasan et al. [2008] minimised the LCCs of a typical detached Finnish house by combining GenOpt and IDA ICE 3.0. The space heating was reduced by 23-49%. For this work, to get design solutions that meet the nZEB standard, TasGenOpt is utilised to find optimised values for the various design variables such as external wall u-values, double/triple glazing, best HVAC measures etc. A range is selected for each of those variables as per typical practise within the literature. As there is no limit to the number of input and output variables with TasGenOpt the retrofit scenarios are easily generated by inputting multiple variables at once. The precise set of parameters to be optimised has been included under each case study, where GenOpt has been used [see sections 4.5-4.5.4 and 5.5-5.5.5].

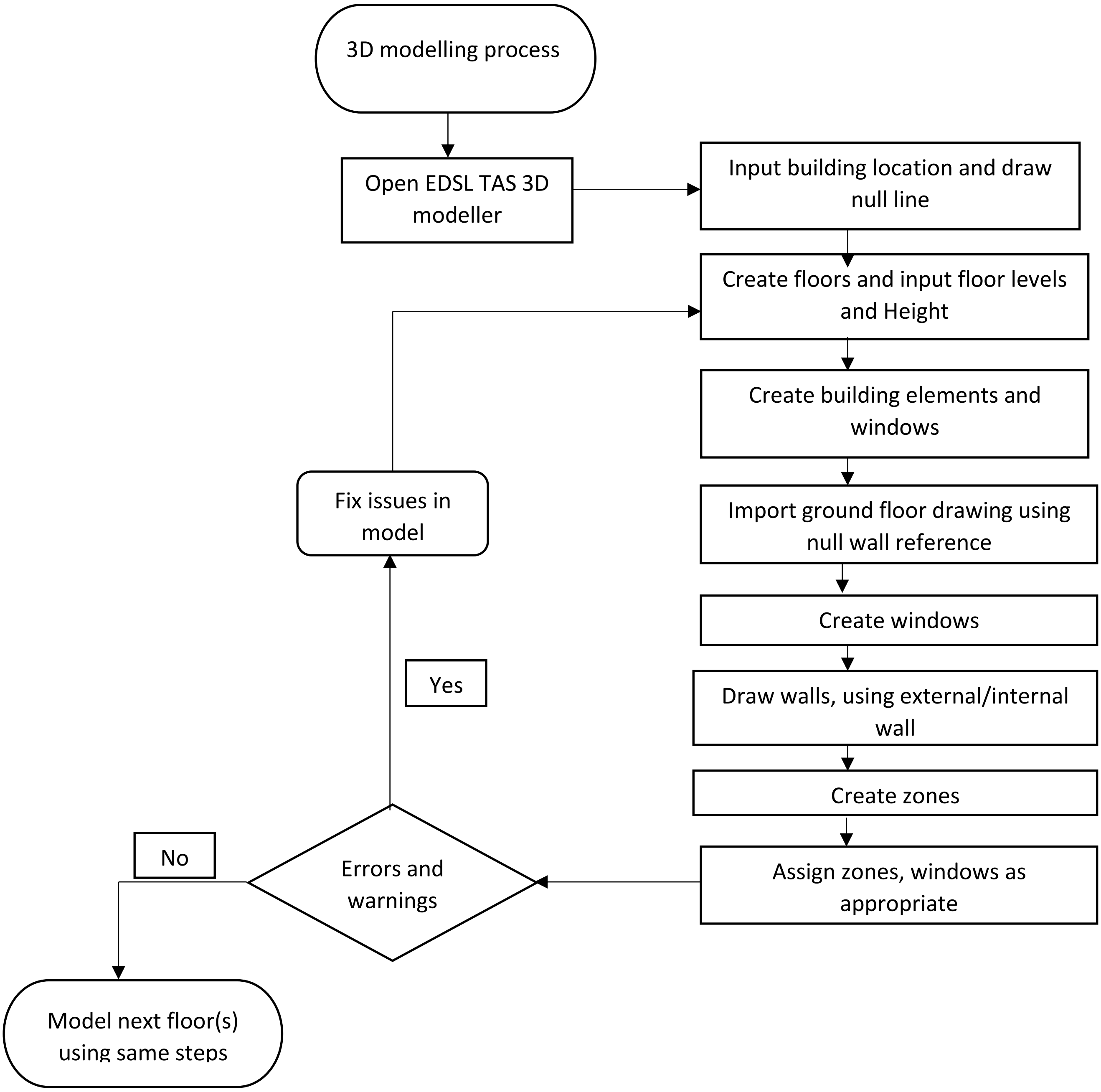


Figure 3. 1: Summary of 3D model creation process

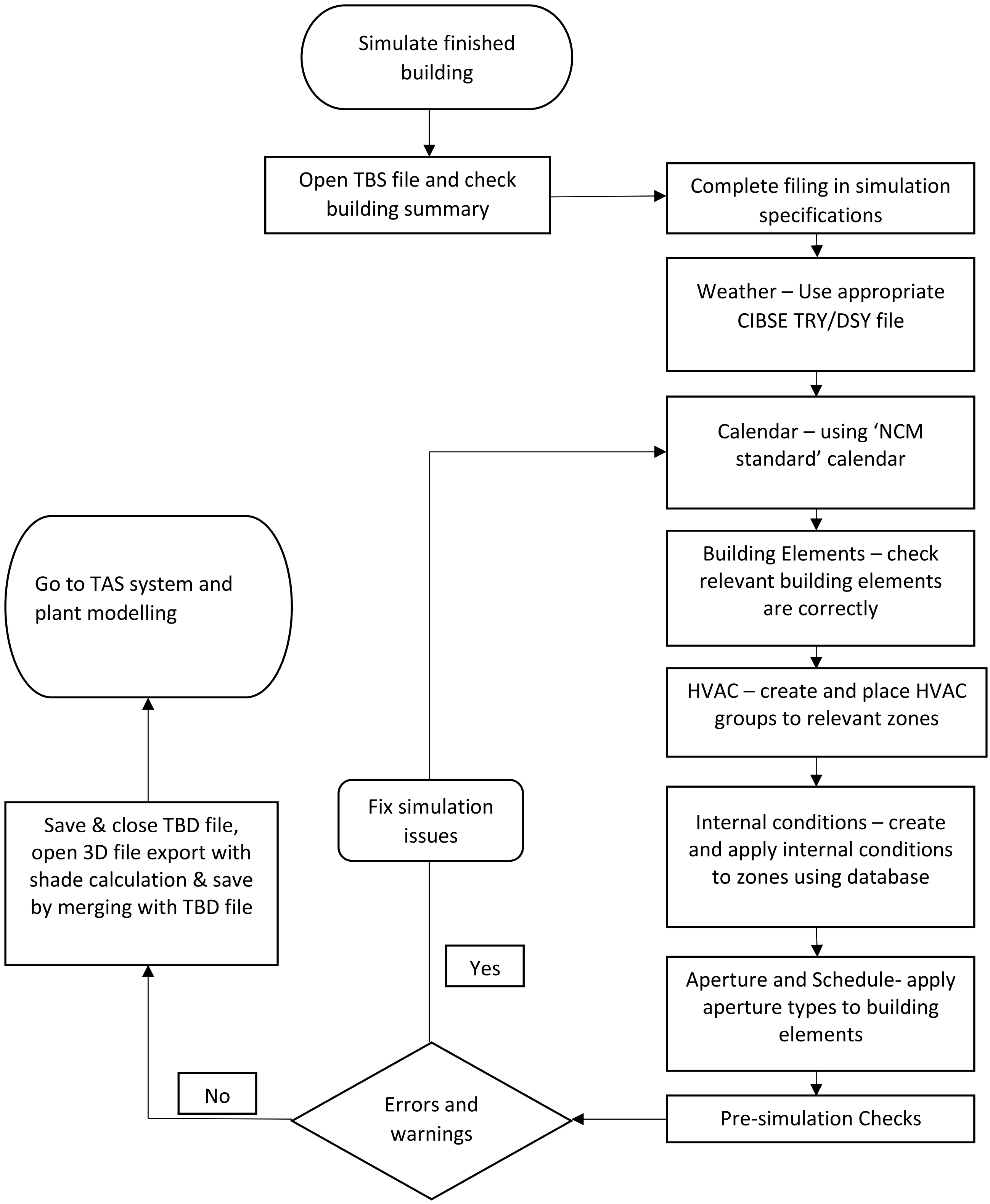


Figure 3. 2: Summary of building simulation process

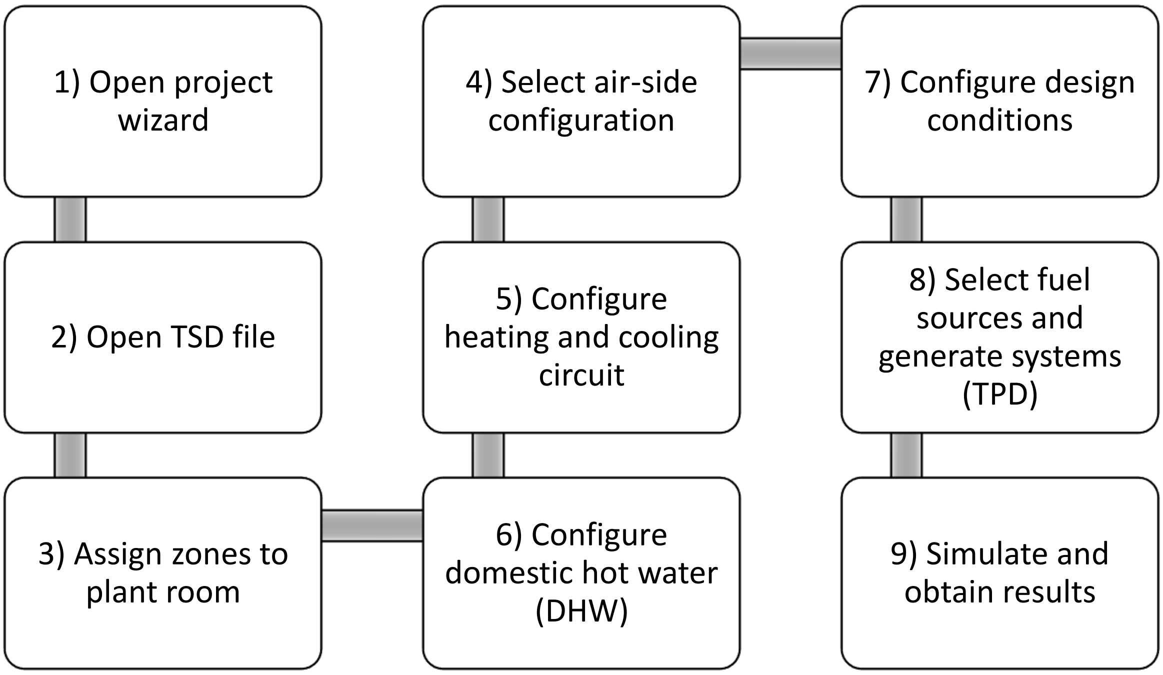


Figure 3. 3: Summary of TasGenopt process

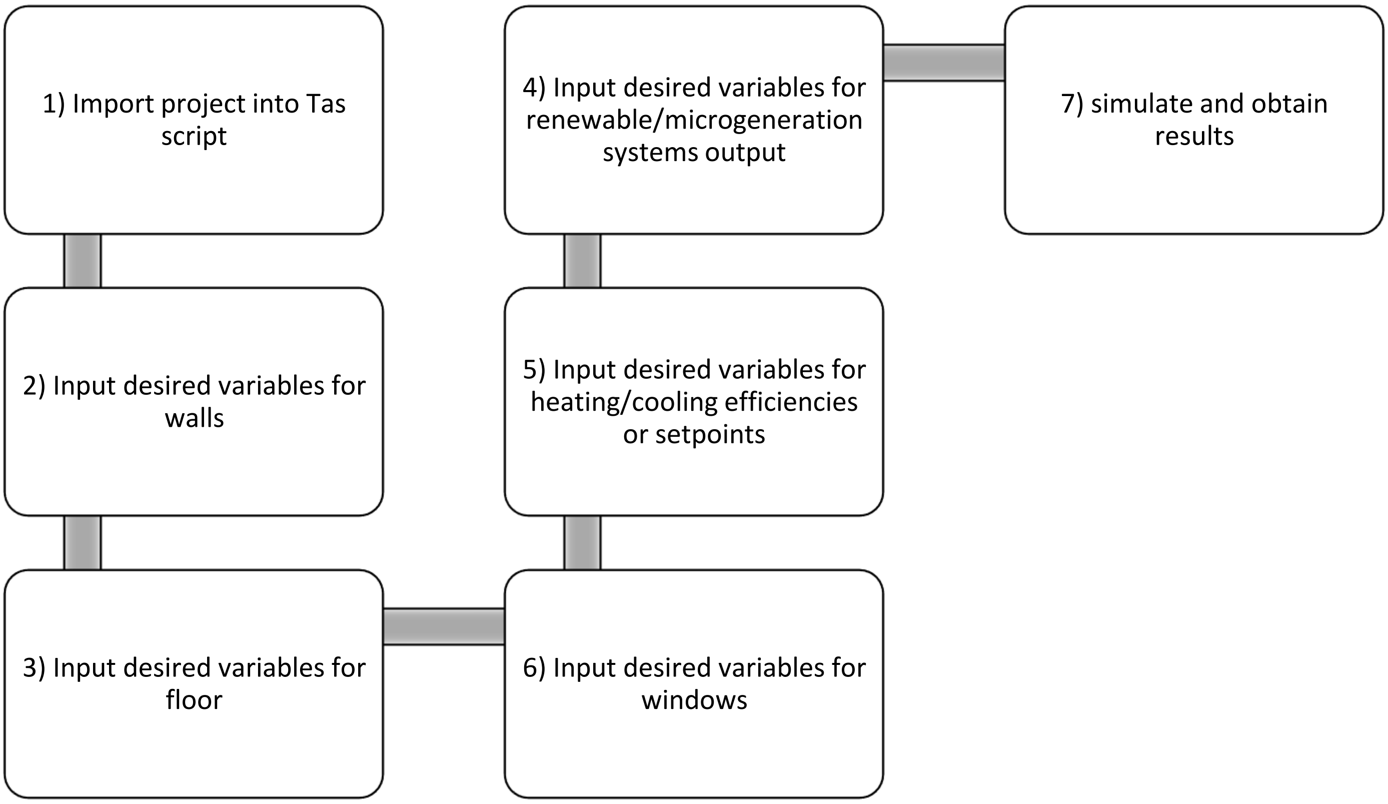


Figure 3. 4: Summary of TasGenopt process

3.3.2. Modelling Assumptions

To successfully select suitable parameters for the model, certain assumptions need to be made:

- Fully adopting the Cibse TRY weather files without any alterations and assuming that they are valid and relevant to the true weather climate of each building
- The national calculation methodology (NCM) database will be used to represent all internal conditions, activity, and occupancy. It will be assumed that these internal conditions are the actual current conditions of the dwelling.
- The automatic simulation of natural ventilation (because of windows, doors, ventilators, and other apertures – relative to their altitude and orientation) will be assumed to be the realistic representation of the actual airflow.
- Whilst it is well documented that many GHGs contribute to polluting the environment, it is agreed upon that CO_2 is the key contributor to climate change [DC, 2011]. Accordingly, this work will only take into consideration the amount of CO_2 that design variables can reduce.

3.3.3. Modelling Validation

In order to validate the models created on Tas the actual annual energy consumption of the building (A^{ec}) is subtracted from the modelled energy consumption (M^{ec}); divided by the modelled energy consumption (M^{ec}) and multiplied by a 100 to provide the percentage difference or error between actual and modelled energy consumption [equation 3.1].

$$Percentage\ error = \frac{M^{ec} - A^{ec}}{M^{ec}} x100 \qquad [3.1]$$

3.4. Life Cycle Cost Analysis

3.4.1. Life Cycle Costs: Method and Assumptions

The purpose of conducting the LCCA is to be able to analyse which scenario offers the most profit, in terms of lowest global LCCs and therefore highest net savings. This is in correspondence with the EPBD guidelines which state that member states are to select design solutions with calculated "cost-optimal levels," as discussed earlier. However, when selecting the final solution, it is essential that one finds a *balance* between the 'cost-optimal' solution and the 'near-zero' solution. Many studies have concluded that cost optimality and reaching the nZEB standard are two fundamentally related concepts within the EPBD [Famuyibo, 2012; Ferreira et al. 2013; Paressa et al. 2015; François et al. 2017]. Therefore, if one were to focus on the selection of only a cost-optimal solution, then a near-zero solution will not be reached, and vice versa.

Calculation of global costs may be calculated using the following: the global costs $C_G(\tau)$ which is referred to starting year τ_0 are calculated by taking the sum of the initial investment costs CO_{INIT} for component j, the annual cost for year i which is discounted by the discount factor D_f (and is dependent on the discount rate α) for year i, and the residual value VAL_{fin} of component j in year TC at the end of the calculation period is referred to starting year τ_0 [equation 3.2]. The calculation period is 30 years as recommended by the European Commission Delegated Regulation's guidelines for residential buildings. The residual value refers to the remaining value of a measure or a retrofit scenario until the end of its lifespan. The European Committee for Standardisation (EU CEN) proposes that residual values are calculated by "linearly prorating the initial investment costs." To elaborate, if we take an EEM with a projected useful life of 60 years, with the study period being 30 years, the residual value will be roughly 50% of the initial investment costs of that measure.

$$C_G(\tau) = CO_{INIT} + \left[\sum_{i=1}^{TC} CO_{a(i)}(j)\, x \left(D\_f_{(i)} - VAL_{fin(\tau_{TC})}(j)\right)\right] \qquad [3.2]$$

The real interest rate R_R is affected by the interest and inflation rate $R_{interest,}$ $R_{inflation}$ and is calculated using equation 3.3. As for the discount rate α it can be calculated using equation 3.4. Alternatively, for residential retrofit projects such as this it can be obtained from the Office for National Statistics, which recommends that for projects of 0-30 years a 3.5% discount rate should be adopted.

$$R_R = \frac{R_{interest} - R_{inflation}}{1 + \frac{R_{inflation}}{100}} \quad [3.3]$$

$$\alpha = \left(\frac{1}{1 + \frac{R_R}{100}} \right)^i \quad [3.4]$$

The net present value, NPV_{TC} is a "multiplying factor that aims to figure the reduction of the value at the end of period of calculation" and is calculated according to Equation 3.5. It is essentially the sum of the cash flows discounted based on the discount rate which will reflect the "cost of money over time" [SCSI, 2012]. Furthermore, because the LCCA includes cash flows and costs taking place at various time periods of the life cycle of the dwelling it is essential that all those costs are converted to their present values. The present value factor therefore allows for the comparison of the calculated costs of the LCCA, including the value of projected future costs, based on the current value of money.

$$NPV_{TC} = \begin{array}{c} \Delta_{INIT} + \sum_{i=1}^{TC} \frac{\Delta_{MNT,i}}{(1+\alpha)^i} + \sum_{i=1}^{TC} \frac{\Delta_{RNT,i}}{(1+\alpha)^i} + \sum_{i=1}^{TC} \frac{\Delta_{MSC,i}}{(1+\alpha)^i} + \\ \sum_{i=1}^{TC} \frac{\Delta_{ELEC,i}\, x\, (1+i_e)^i}{(1+\alpha)^i} + \sum_{i=1}^{TC} \frac{\Delta_{GAS,i}\, x\, (1+i_g)^i}{(1+\alpha)^i} \end{array} \quad [3.5]$$

For this work the NPV is split into costs and savings that result from the initial investment (discounted to the time of investment). The NPV is calculated for each scenario and compared to the base-case. The NPV is therefore calculated by summing the (Δ_{INIT}) investment cost; replacement and maintenance costs ($\Delta_{M/RNT}$); miscellaneous costs Δ_{MSC}; in addition to the cost of electricity and gas consumption multiplied by the real energy price increase I_{EP} for year i. The energy price increase rate I_{EP} differs from the inflation rate and is therefore calculated using equation 3.6 where R_{ep} refers to the expected rise in electricity and gas prices which equals 1.60% i_e and 0.70% i_g, respectively [UK Power, 2019]. Current average cost of gas and electricity for the UK is 3.80 and 14.37 pence/kWh [UK Power, 2019].

$$I_{EP} = \frac{(1 + R_{ep})}{R_R + R_{ep}} \left(1 - \frac{1 + R_{ep}}{1 + R_R}\right)^i \qquad [3.6]$$

Using the above formulae, a LCCA tool can be developed using Excel software. Otherwise, there are several LCCA software which could be utilised. For this project Building Life Cycle Cost software will be utilised. BLCC is developed by the National Institute of Standards and Technology (NIST). The software computes the life-cycle costs (in present-value) for the base-case and each alternative retrofit scenario. Furthermore, BLCC calculates additional indicators of cost effectiveness such as the net savings and payback period. The relevant and necessary data such as initial capital costs and operational costs and economic boundaries such as the discount rate and investment period are populated by the user. Once this is done BLCC then calculates the total LCCS for the project alternatives in net present value.

The first step in BLCC is to begin a new project description. This is usually the name of the baseline building (e.g. ‘Hilton Reading’). Within this, the type of building and activities, occupant usage and comfort requirements, types of energy, and any relevant schedules are all included. Furthermore, the energy efficiency of the HVAC systems and plants are all inputted. Following this, the type of investment decision requirement is defined. For this work it is always “select optimal retrofit option.” This refers to the most cost-effective building retrofit alternative. Adding constraints is another important step to populating the file. Constraints can be physical, functional, safety related, building-code relate, and budgetary. For example, if a building cannot have a certain due to financial constraints any retrofit options inputted that do have an option above a certain cost are eliminated.

Following this, the next step is to begin the project alternatives and input the background information. Alternatives that do not satisfy the specifications set out in the project description are eliminated. The study period and all other parameters, and costs are then inputted. See Figure 3.5 for step by step process on how to use BLCC.

As mentioned earlier one of the most significant barriers to obtain a valid and reliable cost analysis is the collection of reliable data for the renovation costs. Two main sources are used to collect cost data for this work, namely, the Department of Energy and Climate Change (DECC) (now the Department of Business, Energy and Industrial Services- BEIS) 2050 pathway calculator: with costs and the UK 'Bestimator' database. The 2050 pathway calculator [See Link 1] is an open source tool that has been developed as a step to help the UK meet its 2050 carbon target. This collective cost database is first of its kind and the approach has already been replicated in other parts of the world (e.g. China, India, Belgium, South Africa, Taiwan, South Korea, and Japan) and some countries (Indonesia and Thailand) have begun drafting their copy. As BEIS continue to develop this database the barrier to obtaining reliable and comparable costs for retrofit projects is set to become lower. However, as the database is still being developed and improved other sources are also used for verification of costs and obtaining of costs where necessary. These range from generic UK construction cost database to actual costs from supplier websites.

[1] https://d.docs.live.net/9a3ea0f7674dcedf/Documents/2050-calculator-with-costs.xlsx

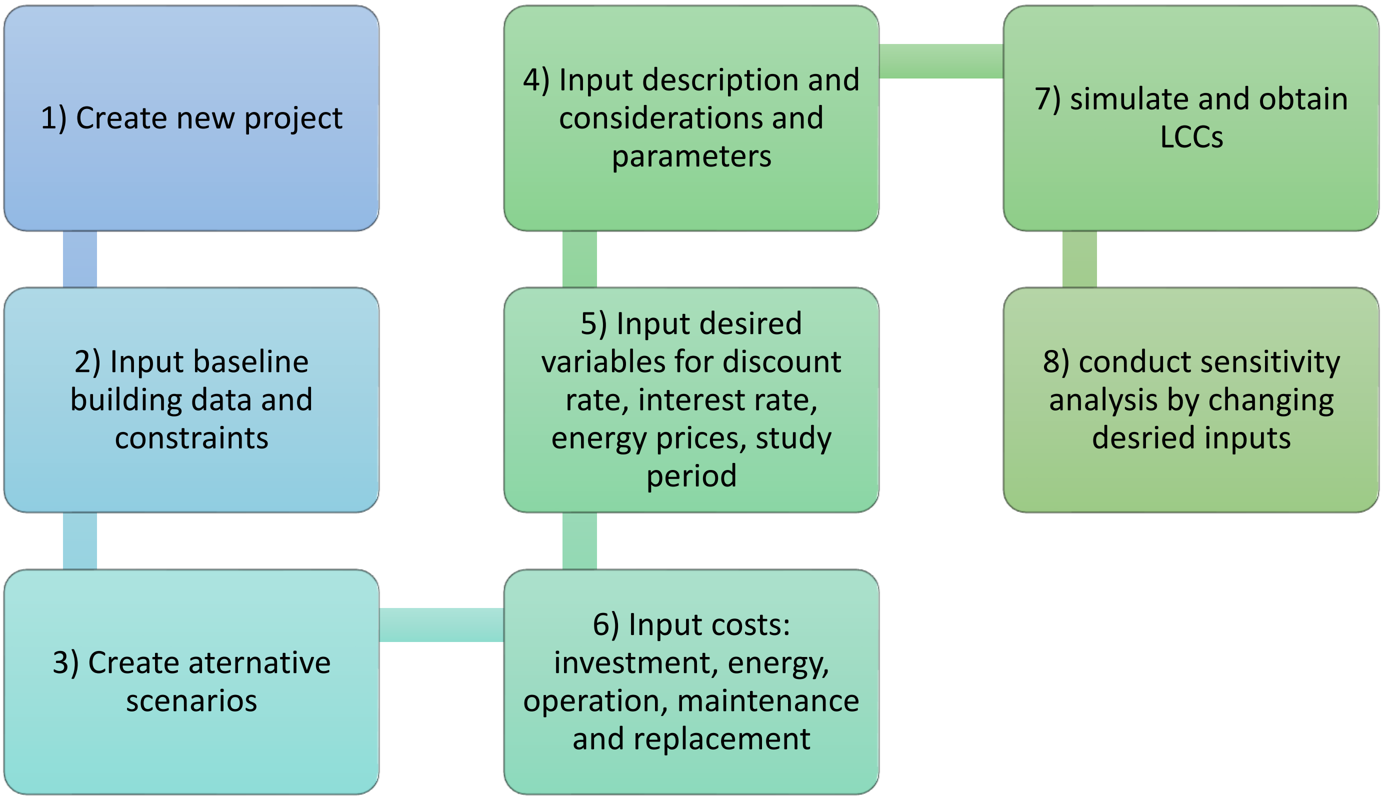
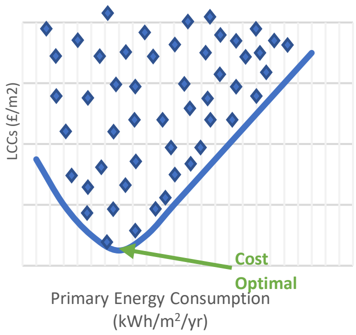


Figure 3. 5: Summary of BLCC software process

3.4.2. Cost-Optimal Solution

Per EPBD guidelines "Framework Regulations for calculating cost-optimal levels of minimum energy performance requirements (No.244/2012)," individual EEMs need to be selected and then grouped into retrofit packages or sets. These sets are the retrofit scenarios of the various buildings, with one scenario being the existing state of the building. The directive has proposed a 'cost-optimal range'. To identify the cost optimal level, the LCCs of the various retrofit scenarios will be compared to the PEC (kWh/m²/yr) to create a cost-optimal curve as illustrated in Figure 3.6. The lowest point along this curve is the cost-optimal retrofit scenario.



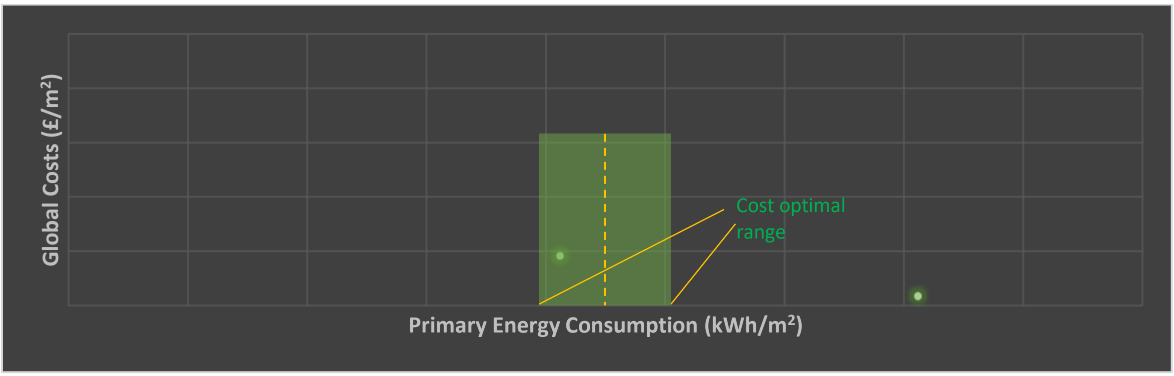


Figure 3. 6: Reproduced example of a cost-optimal curve

3.5. Overheating Criteria

In the design of non-air-conditioned spaces there have been no detailed guidance on defining and monitoring the risk of overheating within the UK. However, Cibse guide A defines overheating as indoor building temperature that exceeds 28^{o}C for living areas and 26^{o}C in bedrooms for more than 1% of occupied hours per year. This is the deterministic fixed operative temperature threshold approach to analysing overheating risk as shown in Table 3.1. This approach however has received criticism that it does not consider the severity of overheating within the space and is considered limited.

The equation for comfort temperature T_{comf} is shown by Equation 1b, where, T_{rm} is the exponentially weighted running mean daily mean outside air temperature. The running mean daily mean outside air temperature is calculated using Equation 1.2b where α is a constant (0.8) and $T_{od\ldots}$are the daily mean outdoor temperatures for the day of interest followed by the previous day(s) [Equation 1.3b].

Another approach to overheating analysis is introduced and this is based on the adaptive thermal comfort approach by the British Standard European Norm BS EN 15251:2007. This is based on the smart controls and thermal comfort (SCATS) monitoring study carried out across five EU countries. The BS EN 15251 underpins the Cibse TM52 [The Limits of Thermal Comfort: Avoiding Overheating in European Buildings'] overheating guidance within the UK which is used to assess the performance of naturally and mechanically ventilated spaces. It is based on three criteria: hours of exceedance, weighted exceedance and upper temperature limit as shown in Table 3.2. A dwelling is considered overheated if any two of the three criteria are exceeded. In more detail, the TM52 criteria is based upon three sets of thresholds known as category I, II, and III. These categories assign a maximum acceptable temperature of varying degrees above the comfort temperature for naturally ventilated buildings as show by Equations 2b-4b. The category I threshold applies to spaces that are occupied by very sensitive and fragile persons with special requirements, such as the disabled, sick, very young, and the elderly. Category II threshold applies to new buildings and renovations and category III applies to existing buildings. Category I is generally considered the stricter of the three categories.

Similar to the TM52 criteria is the "TM59: 2017 Design methodology for the assessment of overheating risk in homes." The TM52 criteria can be used to assess any type of building, meanwhile, the TM59 criteria is more specifically tailored to assessing the risk of overheating in residential buildings. To summarise, the two overheating criteria set out by TM59 are:

1. Criterion 1 for living rooms, kitchens, bedrooms: the number of hours during which DT is greater than or equal to one degree (K) during the period May to September inclusive shall not be more than 3 percent of occupied hours.
2. Criterion 2 for bedrooms: during the sleeping hours the operative temperature in the bedroom from 10pm to 7am shall not exceed 26^{o}C for more than 1% of annual hours (33 hours).

Bedrooms must pass both requirements.

Although the TM59 criteria recommends that future weather data files such as 2050s/2080s are run it is not a set requirement that the building passes. On the other hand, it is necessary that the building passes under the 'current' and 2020s High emissions, 50th percentile DSY 1.

Table 3. 1: Cibse Guide A overheating criteria

Space	**Operative temperature for indoor comfort in summer (^{o}C)**	**Benchmark summer peak operative temperature (^{o}C)**	**Overheating criterion**
Living room	25	28	1% annual occupied hours over operative temp. of 28 ^{o}C
Bedroom	23	26	1% annual occupied house over operative temp. of 26 ^{o}C; sleep may be impaired above 24 ^{o}C

Table 3. 2: Cibse TM52 overheating criteria

$\Delta T = T_{op} - T_{comf}$	[1b]
$T_{comf} = 0.33T_{rm} + 18.8$	[1.2b]
$T_{rm} = (1-\alpha)(T_{od-1} + \alpha T_{od-2} + \alpha^2 T_{od-3} \ldots)$	[1.3b]
$Catergoy\ I: T_{comf} = 0.33T_{rm} + 18.8 + 2$	[2b]
$Categroy\ II: T_{comf} = 0.33T_{rm} + 18.8 + 3$	[3b]
$Category\ III: T_{comf} = 0.33T_{rm} + 18.8 + 4$	[4b]

Table 3.2 1: Cibse TM52 overheating criteria

Criterion	***Notes***
Hours of exceedance (H_e)	Number of Hours (H_e) during which ΔT is ≥ 1°C during the cooling season (May-September) should not be more than 3% of the total occupied hours
Daily weighted exceedance (W_e)	The daily limit set for weighted exceedance (W_e) shall be ≤ 6 in any one day to allow for the severity of the overheating: $W_e = (\sum h_e) x W_F = (h_{e0}\, x0) + (h_{e1} x1) + (h_{e2} x2) + (h_{e3} x3)$. Where, W_F is the weighting factor is equal to 0 if ΔT < 0. Otherwise $W_F = \Delta T$, and h_{ey} is the times (Hrs) when W_F = y.
Upper limit temperature (T_{upp})	The absolute maximum value for an indoor operative temperature ΔT should not exceed 4°C

3.6. Chapter Summary

This chapter established that the research questions of this thesis can all be effectively addressed using a quantitative methodology. The thermal analysis simulation software Tas is explained and a justification is provided for selection of this software. A step-by-step explanation of the modelling, process is provided. It was also established that the LCCA is going to be carried out using building life cycle cost software (BLCC) to compute the life cycle costs (LCCs), net savings, and payback period. A sensitivity analysis is methodology is also presented and this will be used to identify uncertainty relative to the retrofit scenarios. The EPBD's cost-optimal range methodology is discussed as it will be employed to select the cost-optimal solution. To investigate the risk of overheating associated with reaching the nZEB standard the CIBSE TM59 Overheating Criteria is utilised. All these different methodologies will be used in the following 2 chapters to address the research questions and identified gaps in knowledge.

CHAPTER 4: RESIDENTIAL CASE STUDIES

4. Chapter Introduction

This chapter explores all the residential case studies that have been modelled and investigated to explore the research questions. It presents the main results through various figures and tables; it then analyses and discusses the main findings to answer the research questions.

4.1. Case Study 1

4.2. Building Description

The first residential building analysed is a four-bedroom detached dwelling located in Bracknell, Berkshire, England. Figures 4.1-4.2 show the floor plans and the Tas 3D model of the dwelling. According to the English Housing Survey [2018], 35 percent of the British population live in detached houses. Meaning that this type of dwelling is the second most common type of residential dwelling (with semi-detached being the most common) across the UK, thereby making it an excellent representative as a case study. Furthermore, this dwelling is built pre-1990, meaning that the standards to which the house is built are below today's targets, making it more challenging to retrofit.

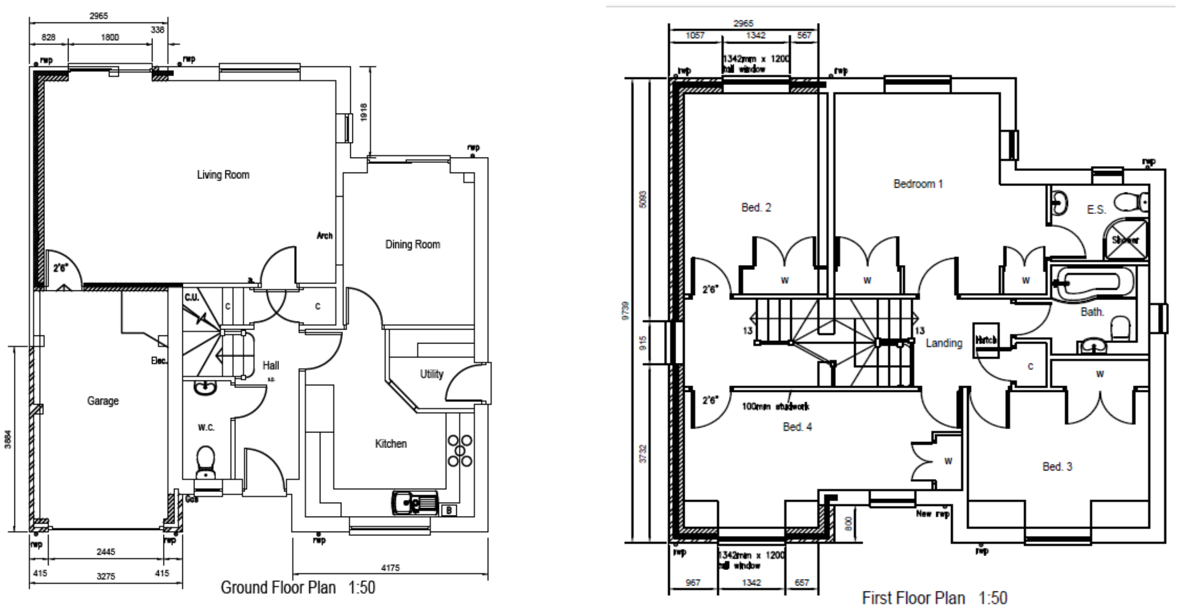
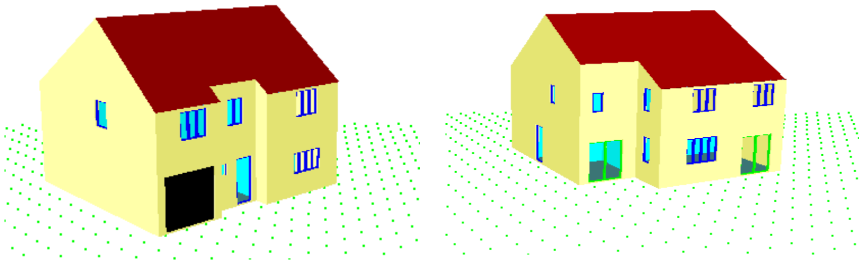


Figure 4. 1: Floor plans of the case study building with a scale of 1:50



4a) Front elevation 4b) Rear elevation

Figure 4. 2: Tas 3D Modelling results

4.3. Baseline Model

Looking Table 4.1, it can be seen that there is a substatnial difference between the case study's performance values and the nZEB target. As mentioned previously, these values reflect the amount of energy that is required to maintain a comfortable internal temperature and to meet the daily heating, cooling, elecrticity, and DHW usage of the occupants. The values obtained as a result of simulation suggest that current occupants require a large amount of energy to achieve and maintain a comfortable internal temperature.

Table 4. 1: Building fabric results of baseline model

	nZEB	**Case study – Tas initial model simulation**
External Wall U-value (W/m^2k)	0.11	0.32
Ground floor U-value (W/m^2k)	0.10	0.57
Window U-value (W/m^2k)	0.80	3.45
Roof U-value (W/m^2k)	0.13	0.29
Air permeability rate ($m^3/h/m^2$ @50Pa)	1.0-3.0	6.00
Annual Primary Energy Consumption (kWh/m^2)	44	135.91
Annual Carbon Emissions ($KgCO_2/m^2$)	10	51.73

Another important aspect of the results that needs to be taken into consideration is the annual primary energy consumption of the dwelling. The annual primary energy consumption is affected by carbon emission factors for the different fuel types and provides a value for the energy used per year to keep the building at 19^{o}C and above [CIBSE, GPG 303, 2000]. Houses with very poor insulation can reach values of 400kWh/m^2/year. The reason for this high value is because generally 1 litre of fuel oil is required to heat a square metre of a building per year [Seiders et al. 2007]. However with a careful retrofit strategy this value can be considerably lowered.

4.4. nZEB Simulations

4.4.1. Thermal Insulation

The existing insulation for the roof and the external cavity wall is an 85 mm mineral wool quilt. This is the most common form of insulation used in regular UK dwellings due to its simple installation and inexpensiveness. The ground floor insulation is 35 mm expanded polystyrene (EPS). Looking at the initial results generated by the building it can be concluded that the insulation of all those building elements is insufficient.

Table 4.2 shows that an implemented increase of the thickness of the thermal insulating layer can contribute to a reduction in U-values. Furthermore, EPS did not only have the lowest U-values in comparison to wool insulation, it also contributed to significantly lower annual primary energy consumption, and lower CO_2 emissions. Previous studies have demonstrated that whilst increasing the thickness of the thermal material is favourable, it is essential that an 'optimal thickness' is selected (Ma and Wang 2012). This is because, further increase beyond the optimal thickness will not have any additional benefit for reducing U-Value and primary energy consumption. Therefore, one further simulation using EPS is conducted with varying thickness as shown in rows 7 and 8. Once the simulation with 130 mm thickness is conducted, it is apparent that this is the optimal thickness for this building and will therefore be the adopted value in the final analysis of the building.

Table 4. 2: U-value results of various thickness of EPS, mineral wool batt, and rock wool

	Material	External Wall U-Value (W/m²k)	Roof U- Value (W/m²k)	Ground Floor U- Value (W/m²k
1	EPS, 85mm	0.32	0.29	0.18
2	EPS, 150mm	0.15	0.14	0.12
3	Mineral Wool Batt, 85mm	0.38	0.31	0.22
4	Mineral Wool Batt, 150mm	0.25	0.22	0.16
5	Rock Wool, 85mm	0.38	0.34	0.24
6	Rock Wool, 150	0.24	0.23	0.17
7	***EPS, 100mm***	***0.24***	***0.21***	***0.15***
8	***EPS, 130mm***	***0.15***	***0.16***	***0.12***

4.4.2. Ventilation

Airtightness can be considered one of the most important aspects to ensure that the energy efficiency of the building can reach its full potential. Even if a high level of thermal insulation is reached and a passive solar heating system is incorporated, their benefits will be lost if the "warm air can leak out and cold air can leak in" [Anderson, 2011]. A 'reasonable' limit has been set by the building regulations (Part L) as 10 $m^3/h.m^2$ at 50 Pa. An energy efficient building should be between the range of 1 to 3 $m^3/h.m^2$ at 50 Pa. Mechanical ventilation (MV) in this case is a requirement that needs to be provided to avoid poor air quality as the airtightness value is very low [Ayoub et al. 2017]. Currently, ventilation in the dwelling is natural passive ventilation as this is achieved by simply opening windows and doors. The measured air permeability level as shown in Table 4.3 is 6 $m^3/h.m^2$ at 50 Pa with an infiltration level of 0.250 air changes per hour (ACH). Whilst this does not exceed the limit set by the building regulations (Part L), it is still underperforming compared to the target for nZEBs. Although this method of ventilation requires no direct energy to operate, it still accounts for one third of the space heating energy demand, due to the large volume of warm air exiting the property [Ayoub et al. 2017]. Consequently, with 'heating' being the largest contributor to annual primary energy consumption, incorporating mechanical ventilation will provide fresh (pre-warmed air), which will in turn reduce space heating demand.

Although ventilation systems added cooling loads to the primary energy consumption and carbon emissions, the overall values are still much lower in comparison. The simulation runs with various ventilation systems shown in Table 4.3 indicate that incorporating a ventilation system in the dwelling will have a significantly positive contribution to reducing primary energy consumption and carbon emissions. The largest difference for primary energy consumption and carbon emissions is 12.35% and 14.17%, respectively. If mechanical ventilation with variable refrigerant flow (MVRF) is to be adopted with the other measures, it would have the largest contribution to improving energy efficiency of the building and reduce emissions. It is also worth noting that this system has limited space requirements which makes it ideal for incorporating into older buildings undergoing retrofitting.

Table 4. 3: Simulation results of various ventilation systems and its comparison to baseline model

Type of Ventilation	Air Permeability rate ($m^3/h/m^2$ @50Pa)	Heating	Cooling	Total	Heating	Cooling	Total
		Primary Energy Consumption (kWh/m^2)			*Carbon Emissions ($kgCO_2/m^2$)*		
Whole-house Ventilation	3	56.21	0.89	120.76	17.63	1.72	48.30
Mechnical Ventilation (with VRF)	3	55.42	0.54	119.12	16.08	1.29	44.40
Baseline Model	***6***	***60.35***	***0.00***	***135.91***	***20.72***	***0.00***	***51.73***

4.4.3. Lighting

The building currently uses incandescent lighting as its main source of lighting. The simulated results shown in Table 4.4 demonstrate that incorporating either LEDs or CFLs will further contribute to a reduction in primary energy consumption and carbon emissions. Initially LEDs are more expensive than CFLs, however in the long-term they are more cost-effective and have a longer life-span (Figueiredo and Martin 2010). Therefore, the existing incandescent lights will be replaced with LEDs, which are more efficient and consume less power for similar illumination intensity.

Table 4. 4: Simulation results of various lighting systems and controls and its comparison to baseline model

Type of Lighting System/Control	**Lighting**	**Total**	**Lighting**	**Total**
	Primary Energy Consumption(kWh/m²)		***Carbon Emissions (kgCO₂/m²)***	
LED	12.23	126.37	4.92	45.14
CFL	13.45	129.56	5.65	49.30
Baseline Model	*15.69*	*135.91*	*6.07*	*51.73*

4.4.4. Glazing

The windows and entrance doors are wooden framed constructed from an uncoated double glazed (air filled) frame with an overall heat transfer coefficient of 2.55 W/m^{2}K. The results in Table 4.5 show that incorporating triple glazing provides a 42.17% decrease of U-value and 22.64% decrease in average U-value in comparison to the baseline model. Therefore, triple glazing will be selected to undergo simulation for the final analysis.

Table 4. 5: Simulation results of various types of glazing and its comparison to baseline model

Type of Glazing	**Air Permeability rate (m^3/h/m^2 @50Pa)**	**Windows**	**Average**
		U-Value (W/m^{2}k)	
Double Glazing, Air Filled, Low-e	4.5	2.20	0.60
Triple Glazing, Argon Filled, Low-e	3.0	0.83	0.53
Baseline Model (4-6-4 Uncoated Glass, Air filled)	*6.0*	*3.45*	*0.84*

4.4.5. Renewable/Microgeneration Systems

The simulated results in Table 4.6 show that solar panels are the most effective at reducing carbon emissions and improving energy performance of the dwelling. The solar panels have been selected to be installed on the roof of the building. This is because, with current technology, this is one of the most efficient ways to generate electricity using solar energy. A 20% efficient 4kW module with solar battery storage is to be used; each panel is made of a 'Monocrystalline silicon solar cell.' Amongst commercially available solar panels, Monocrystalline ones, have the highest energy efficiency and longest life expectancy of 25-30 years (Visa 2014). Therefore, although they may seem more expensive initially, in the long term they will offer the most value in terms of energy and cost efficiency.

Table 4. 6: Simulation results of various renewable and microgeneration systems and its comparison to baseline model

Type of Renewable/ Microgeneration System	**EPC Rating**	**CO_2 Emission *($kgCO_2/m^2$)***	**Primary Energy Consumption (kWh/m^2)**
4kW Solar Panel	B	22.16	67.34
4kW Micro-Wind Turbine	B	24.54	89.41
4kWe Micro-CHP	B	29.13	73.19
Baseline Model	*D*	*51.73*	*135.91*

4.4.6. Results of Final Selected Design Variables

The selected design variables were finally implemented in the building altogether. This resulted in a reduction of the building's annual primary energy consumption of 92.64 kWh/m^2 (68%). The greatest savings after this were achieved for the annual reduction in carbon emissions was 85% and 43.76kg/CO_2. Following this step-by-step retrofit approach offered valuable insight into the performance of the dwelling pre- and post-retrofit for individual measures and overall. Being able to compare the impact of each individual measure on its op indicator and then by combining the best performing measures the nZEB standard was easily achieved for this pre-1990s dwelling.

Following the definition set out in the literature review, the building is connected to an electricity grid to fulfil the basic requirement of a nZEB. Initially, the dwelling had no renewable or microgeneration system in place, therefore, no displacement of electricity occurred. However, the incorporation of the PV panels, concurrently, introduced the factor of 'Displaced Electricity.' According to the Building Regulations, electricity displaced from the grid is a value that is used when crediting on-site generation systems. This is not limited to renewables and can include CHP/trigeneration systems. It is this displacement that highlights the substantial contributions offered by such measures. Once the displaced electricity values were considered, the dwelling was able to easily reach the compliance levels as shown by the total values in Table 4.7.

Table 4. 7: Various building fabric, annual carbon emissions, and annual energy consumption results of the retrofitted building and its comparison to baseline model and NZEB targets

	nZEB Targets	**Retrofitted**	**Baseline model**
External Wall U-value (W/m^{2}k)	0.11	0.15	0.32
Ground floor U-value (W/m^{2}k)	0.10	0.12	0.57
Window U-value (W/m^{2}k)	0.80	0.83	3.45
Roof U-value (W/m^{2}k)	0.13	0.16	0.29
Air permeability rate (m^3/h/m^2 @50Pa)	1.0-3.0	2.5	6.0
Annual Primary Energy Consumption (kWh/m^2)	44	43.27	135.91
Annual Carbon Emissions (KgCO_2/m^2)	10	7.97	51.73

4.5. Life Cycle Cost Analysis

To select individual numerous EEMs and create retrofit scenarios that meet the nZEB target whilst keeping the number of simulations conducted to a minimum TasGenOpt is utilised. Table 4.8 is showing a summary of the set of the set of parameters that are specified and Table 4.9 is showing a summary of the selected scenarios that meet the nZEB target and are categorised based on the above considerations [EC 2017; Tas, 2018].

Table 4. 8: Summary of set parameters for TasGenOpt

Parameter	Unit	Low bound	High bound
Wall U-value	W/m^2K	0.12	0.18
Floor U-value	W/m^2K	0.10	0.16
Roof U-value	W/m^2K	0.10	0.16
Windows U-value	W/m^2K	0.64	0.97
Permeability rate	$m^3/h/m^2$ @50Pa	2.0	3.0
Lighting efficacy	lm/W	60	80
Energy Production	%	40	50

Table 4. 9: Summary of scenarios selected to undergo simulation

Scenario	Energy Efficient Measures (EEMs) -NCM constructions database v 5.2.tcd					
	EEM1 (Thermal Insulation)	EEM2 (Ventilation)	EEM3 (Heat/ Domestic Hot Water -DHW)	EEM4 (Lighting)	EEM5 (Glazing)	EEM6 (Renewable/Microgeneration Systems)
E0 (Baseline)	External wall: 85mm mineral wool quilt Roof: 50mm mineral wool quilt Ground floor: 35mm Expanded polystyrene (EPS)	Natural Ventilation	Old gas boiler	Incandescent	Uncoated glass, air filled	N/A
E1 (Energy efficient -but not nZEB)	External wall: 85mm mineral wool quilt Roof: 50mm mineral wool quilt Ground floor: 35mm EPS	Natural Ventilation	Low Temperature Hot Water (LTHW) boiler	Incandescent	Double Glazing, Air filled, Low-e	2kW Solar thermal heating (Flat collectors)
E2 (Energy efficient -but not nZEB)	External wall: 85mm mineral wool quilt Roof: 50mm mineral wool quilt Ground floor: 35mm EPS	Natural Ventilation	High Efficiency gas boiler	Incandescent	Double Glazing, Coated glass, Argon filled	2kW Solar panels
E3	External wall: 95mm Rock Wool Roof: 95mm XPS Ground floor: 140mm XPS	Mechanical Ventilation: Natural inlet and mechanical extract	8kW Ground Source heat pump (electric)	LED + Auto Presence detection	Triple Glazing, Argon filled, Low-e	Monocrystalline Solar panels (roof) - 16% efficient 3kW module (with electricity storage)
E4	External wall: 95mm Mineral wool batt Roof: 95mm Mineral wool batt Ground floor: 100mm mineral wool	Mechanical Ventilation with heat recovery (MVHRV)	High Efficiency (gas) Boiler	CFL + Auto presence detection	Triple Glazing, Air filled, Low-e	Monocrystalline Solar panels (roof) - 20% efficient 4kW module (with electricity storage)
E5	External wall: 120mm Glass wool quilt Roof: 95mm Glass wool Ground floor: 150mm mineral wool	Mechanical Ventilation with energy recovery ventilator	High Efficiency (gas) Boiler	LED	Double Glazing, Argon filled, Low-e	Micro-CHP 2kWe with heat recovery system
E6	External wall: 100mm EPS Roof: 95 mm XPS Ground floor: 60 mm XPS	Mechanical Ventilation with variable refrigerant flow (VRF)	6kW Ground Source Heat pump	Halogen incandescent (with dimmers)	Triple Glazing, Argon filled, uncoated	Monocrystalline Solar panels (roof) - 16% efficient 3kW module
E7	External wall: 120mm EPS Roof: 100mm XPS Ground floor: 70 mm XPS	Mechanical Ventilation: Mechanical inlet and extract	High Efficiency (biomass) Boiler	CFL	Triple Glazing, Air filled, uncoated	Monocrystalline Solar panels (roof) - 20% efficient 4kW module
E8	External wall: 130mm EPS Roof: 120mm XPS Ground floor: 80 mm XPS	Automatic mixed-Mode ventilation	LTHW (gas) Boiler	LED	Triple Glazing, Argon filled, Low-e	Micro-CHP Fuel Cell System–2kWe
E9	External wall: 160mm EPS Roof: 130mm XPS Ground floor: 90 mm XPS	Mechanical Ventilation with heat recovery (MVHR)	5kW Air Source Heat Pump	LED	Double Glazing, Coated glass, air filled	Monocrystalline Solar panels (roof) - 16% efficient 3kW module (with electricity storage)
E10	External wall: 180mm EPS Roof: 140mm XPS Ground floor: 100 mm XPS	Mechanical Ventilation with VRF	High Efficiency (gas) Boiler	CFL	Double Glazing, Argon filled, low-e	Micro-CHP 2kWe

4.5.1. Operational Energy Use

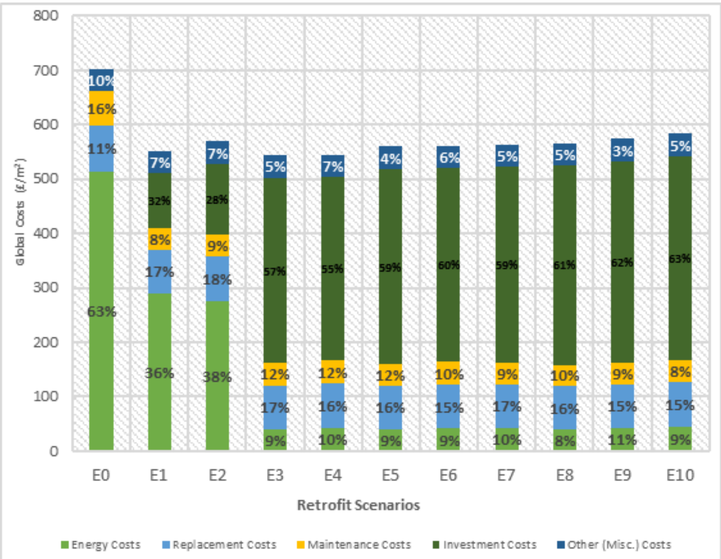
The various scenarios outlined earlier were implemented in the building within Tas. On a purely energy target basis, one can see that scenario E10 is the *optimal* solution. The retrofitting measures incorporated for this scenario resulted in a reduction of the building's annual PEC and carbon emissions of 93.59kWh/m^2 (69%) and 43.57Kg/CO_2/m^2 (84%), respectively. Whilst scenario E1 and E2 did not meet the standard (as expected), their annual PEC 36.61 and 34.54 percent lower than the baseline model. The carbon emissions also decreased by 49% for scenario E1 and 46.24% for scenario E2. The reason why scenarios E1 and E2 were included in this investigation, even though they are not nZEBs, is because the incorporation of those two scenarios will provide valuable insight as to whether the nZEB option is in fact more cost efficient despite the expected higher initial investment costs.

Table 4. 10: The nZEB target values and summary of results for all scenarios

	nZEB	E0	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
External Wall U-value (W/m^{2}k)	0.11	0.32	0.30	0.32	0.17	0.16	0.15	0.33	0.30	0.16	0.15	0.15
Ground floor U-value (W/m^{2}k)	0.10	0.57	0.57	0.56	0.15	0.14	0.13	0.13	0.14	0.14	0.12	0.10
Window U-value (W/m^{2}k)	0.80	3.45	2.93	2.70	0.80	0.95	0.81	0.90	1.12	2.65	2.80	2.32
Roof U-value (W/m^{2}k)	0.13	0.29	0.27	0.30	0.12	0.15	0.15	0.17	0.15	0.12	0.11	0.11
Air permeability rate (m^3/h/m^2 @50Pa)	1.0-3.0	6.0	3.5	5.0	2.5	2.2	1.5	2.5	2.5	2.0	1.0	1.0
Annual Primary Energy Consumption (kWh/m^2)	44	135.91	86.15	88.96	45.64	45.82	47.34	46.60	48.79	47.69	45.03	42.32
Annual Carbon Emissions (KgCO_2/m)	10	51.73	26.38	27.81	10.56	9.94	7.73	10.75	10.12	9.59	9.20	8.16

4.5.2. Life Cycle Cost Results

A breakdown of the different costs for each individual scenario has been generated and the sum has been used as the capital investment cost. Possible grants and/or loans were not taken into consideration for this investigation, however, schemes such as the Renewable Heat Incentive (RHI) domestic scheme and the Feed-in-Tariff (FIT) scheme were considered, where applicable. The different elements making up the LCCs for each scenario were sorted into the following categories: 'Energy costs,' 'Maintenance Costs,' 'Replacement Costs,' and 'Initial investment Costs.' Energy costs included fuel and electricity costs (space heating/cooling, DHW heating, lighting, ventilation, and auxiliary). Maintenance and replacement costs involved fabric and systems maintenance and replacements; annual servicing of boilers, CHP, and Mechanical Ventilation (MV) filters; and possible typical servicing and repairs throughout the study period. Miscellaneous costs refer to any investment costs not related to the EEMs; they range from staff fees to planning application costs.



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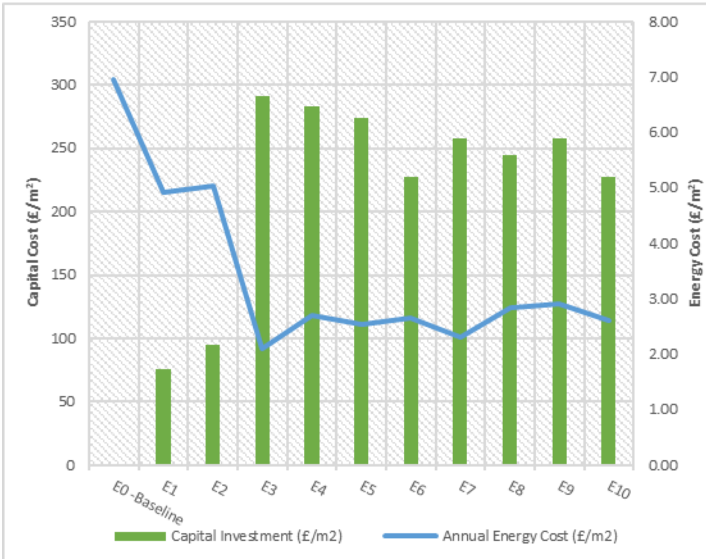


(4.3b)

Figure 4. 3: (a) Breakdown of the various factors of the total LCCS and (b) comparison of investment and energy costs

The comparison of the cost contribution of the different elements of the LCCs shown in igure 4.3a illustrates that for scenarios E3-E10, the capital investment costs, are the most significant cost items over the 30 years calculation period. In comparison to this, the most significant costs in the E0, E1, and E2 scenarios are the energy costs. It is unsurprising to see that the baseline scenario has the highest annual energy costs in comparison to all the other scenarios. The average percentage decrease for the energy related costs between the baseline and the nZEB retrofit scenarios is 61.64%.

Figure 4.3b highlights the relationship between the capital investment and the annual energy costs. That is, the higher the investment cost the higher the potential energy performance of the building. However, even a small investment such as in the case of scenarios E1 and E2 there is still a decrease in the energy costs. This is in consonance with the results from Figure 4.4 which showed a decrease in the LCCs for all the retrofit scenarios. In real life applications however, it is simply not possible to just increase investment costs to reach the standard and budgets are usually limited. Therefore, it is necessary to fully explore the cost analysis so that the true benefits may be investigated, rather than just take into consideration surface values such as the initial investment.

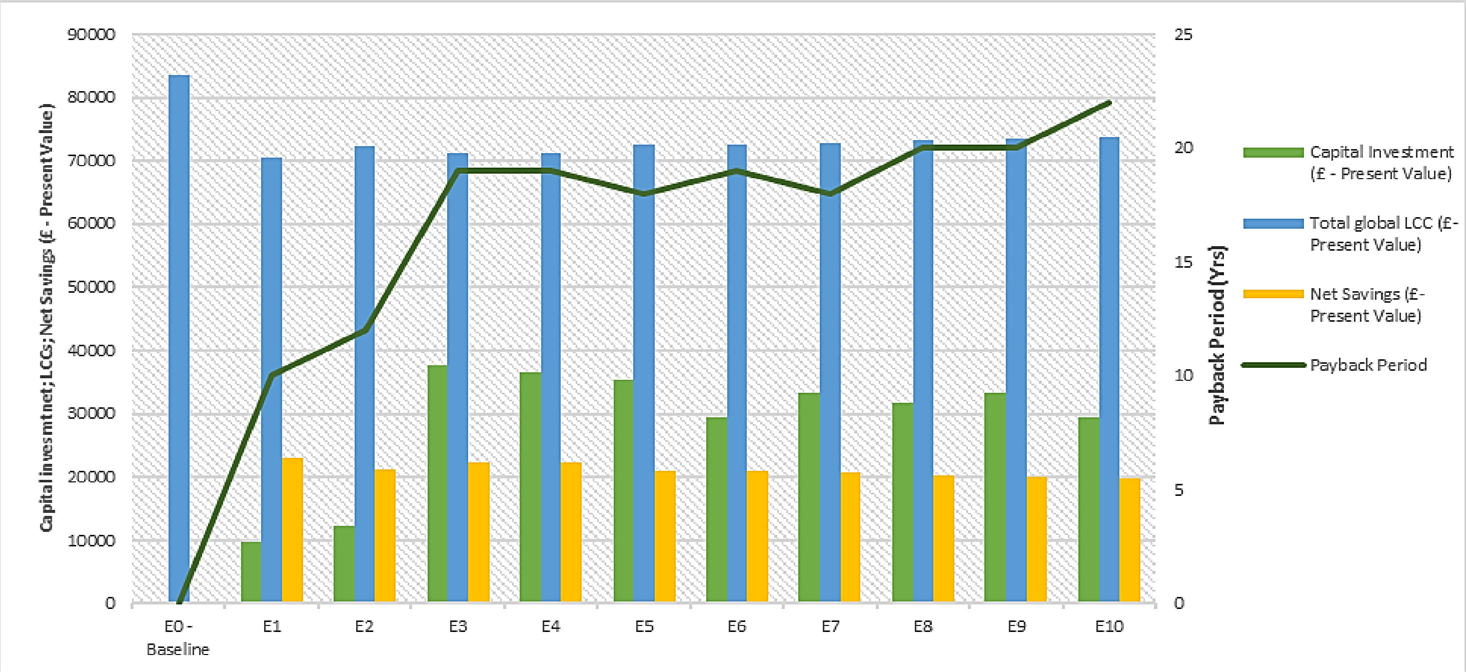


Figure 4. 4: Results of the LCCs calculation for the various scenarios

Looking at Figure 4.4, one can see that the total LCCs of all the different scenarios is lower than the baseline scenario over the 30 years study period. This means that regardless of which scenario is selected for retrofitting, the selected scenario is in fact cost-effective. In other words, not retrofitting the property is the most expensive option and least profitable over the 30 years calculation period.

The above results demonstrate that looking for a solution with the lowest initial capital investment and shortest payback period is an inadequate indicator of actual cost effectiveness. The payback period is often one of the most significant factors for investors when selecting energy efficient solutions, therefore an investor may be more inclined to select a solution with the shortest payback period even if it is the least profitable solution. Scenarios E8, 9 and 10 had the longest payback period of 20 and 22 years, respectively. Scenarios E1 and E2 had a payback period which is approximately half the time span of the nZEB retrofit scenarios. However, whilst it may seem that the payback period analysis does not justify the high costs, it should be noted that this type of analysis does not represent the true economic viability of the measures.

As mentioned earlier, if a solution is to be selected on a purely energy target basis, then scenario E10 is the optimal scenario. Looking at this now from a purely financial basis, the results above would suggest scenario E1 is the 'cost-optimal solution,' it had the lowest LCCs and thereby generated the highest net savings. However, scenario E1 is not a near-zero solution. Followed by this would therefore be scenario E3, which generated the second highest net savings.

Interestingly, the total LCCs of all retrofit scenarios were within a very close range of £70,000-£73,000. This is because the very small initial investment costs of scenarios E1 and E2 meant that energy costs did not decrease significantly in comparison to scenarios E3-E10. Meanwhile, despite the substantial decrease in energy costs for scenarios E3-E10, the high investment costs meant that the total LCCs remained high. What this indicates is that retrofitting the dwelling to nZEB standard may in fact be as cost-effective as the simple retrofit of the dwelling which does not contribute as much to overall energy savings.

4.5.3. Sensitivity Analysis

4.5.3.1. Effect of varying discount rate

One of the most significant considerations in LCCA calculations is the discount rate. The results presented above assumed a discount rate of 3.5%. Neroustou [2014] states that the discount rate "represents a quantification of the uncertainty associated with benefits arising from investments." The discount rate therefore has a significant influence on the LCCs and net savings over the study period. Figure 4.5 demonstrates the effect of increasing the discount rate for the various scenarios. The general trend observed is that as the discount rate value is increased, all retrofit scenarios become impractical. In more detail, for scenarios E1-E2 and scenarios E3-E10, a discount rate of 8% or more and 5% or more, respectively, means retrofitting is no longer cost effective. A discount rate of 2% or less will mean that scenario E3 surpasses scenario E1, in terms of net savings, and becomes the most cost-effective alternative.

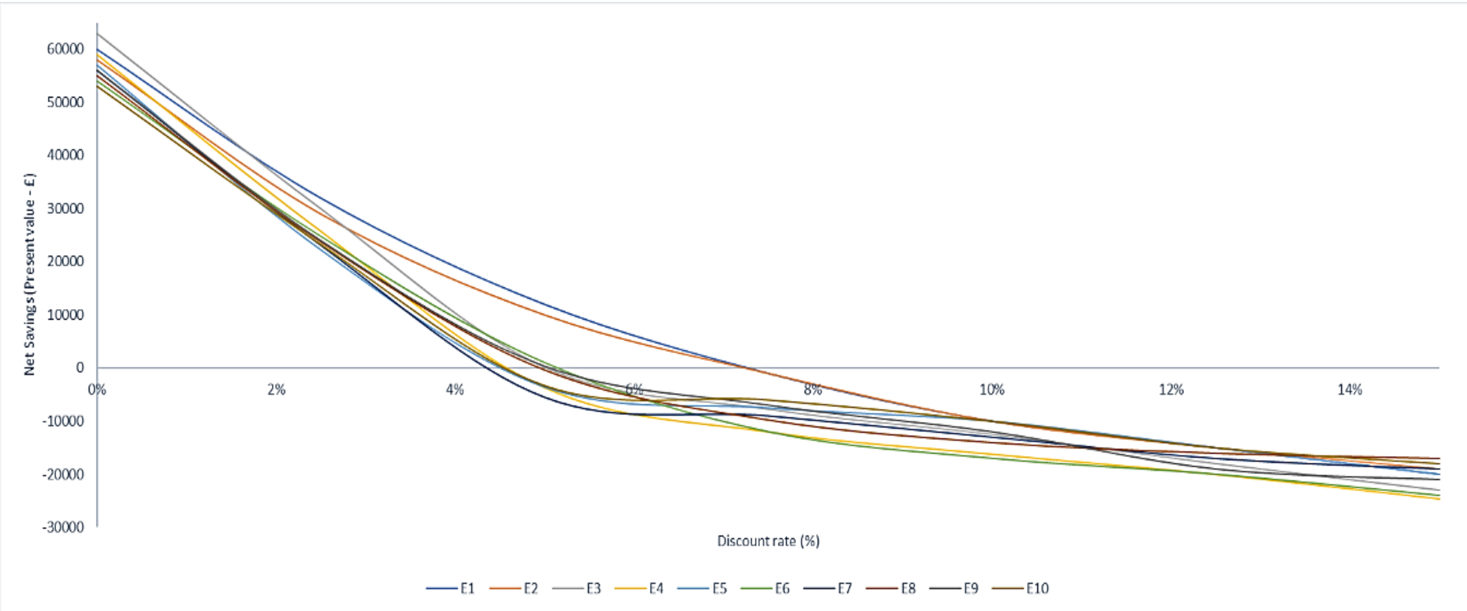


Figure 4. 5: Effect of varying the discount rate on net savings (present value - £)

4.5.3.2. Effect of varying energy/fuel cost

According to UK Power, it has been predicted that there will be a 35% increase in energy demand by 2040, thereby leading to a steadying increase in energy prices. An increase in the fuel price by 5% has meant that all the nZEB retrofit options become more cost effective as shown in Figure 4.6. On the other hand, increasing the energy price meant that scenarios E1 and E2 which are heavily affected by the fuel price, as opposed to the nZEB options, had a significant increase in their energy LCCs. This led to an increase in the overall LCCs which in turn decreased the net savings. Meanwhile, scenarios E3-E10 experienced an increase in net savings as fuel price increased. A decrease in fuel price by 2.5% and more will cause the nZEB scenarios to become uneconomical. This is because the LCCs of the E0 scenario decreases significantly. However, seeing as such fuels are finite resources it is very unlikely that fuel prices will be experiencing any significant reductions compared to current prices. In contrast, an increase of 2.5% or more significantly decrease the economic viability of scenarios E1 and E2. A 5% increase or more means that those two scenarios will no longer be generating any substantial net savings.

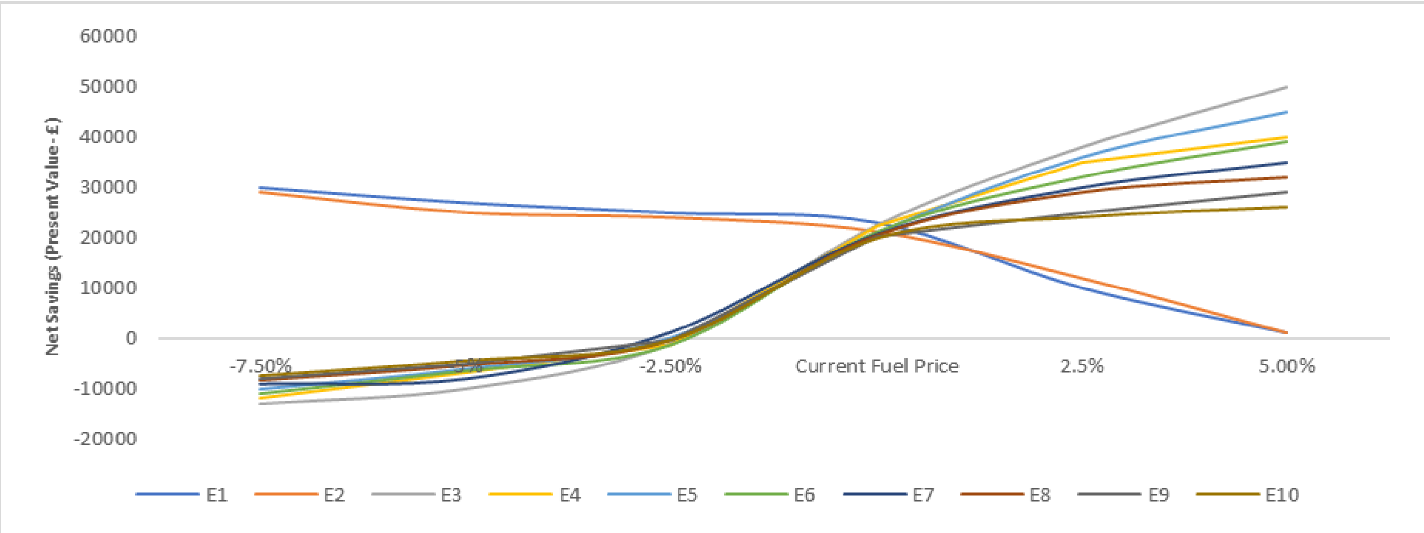


Figure 4. 6: Effect of varying energy/fuel cost on net savings (present value - £)

4.5.3.3. Effect of varying Study Period

From Figure 4.7 it can be seen that a longer study period generates higher overall net savings. The net savings are higher for the nZEB retrofit scenarios in comparison to the scenarios E1 and E2. A study period of 20 years and less means that all nZEB scenarios are no longer cost effective. For the nZEB retrofit scenarios this occurred because even with the substantial reduction in energy costs, the initial investment cost remains too high and cannot be balanced. Meanwhile, a study period of 15 years and less caused scenarios E1 and E2 to become unprofitable, because despite the lower investment costs, the large energy costs eventually led to the total LCCs increase which decreased net savings. Recent statistics have shown that recently homeowners are moving on average 1.8 times over their lifetimes in comparison to 3.6 times prior to 2008 [Finder, 2018; BSA 2018]. This means that homes are being re-mortgaged only once every 20 years, with majority of homeowners not moving at all and spending an average of 39 years in the property [Finder, 2018; FCA, 2018]. Projections estimate that this figure will only increase with rising house prices across the UK. Therefore, for the average UK homeowner a study period of 30 years and more should be considered.

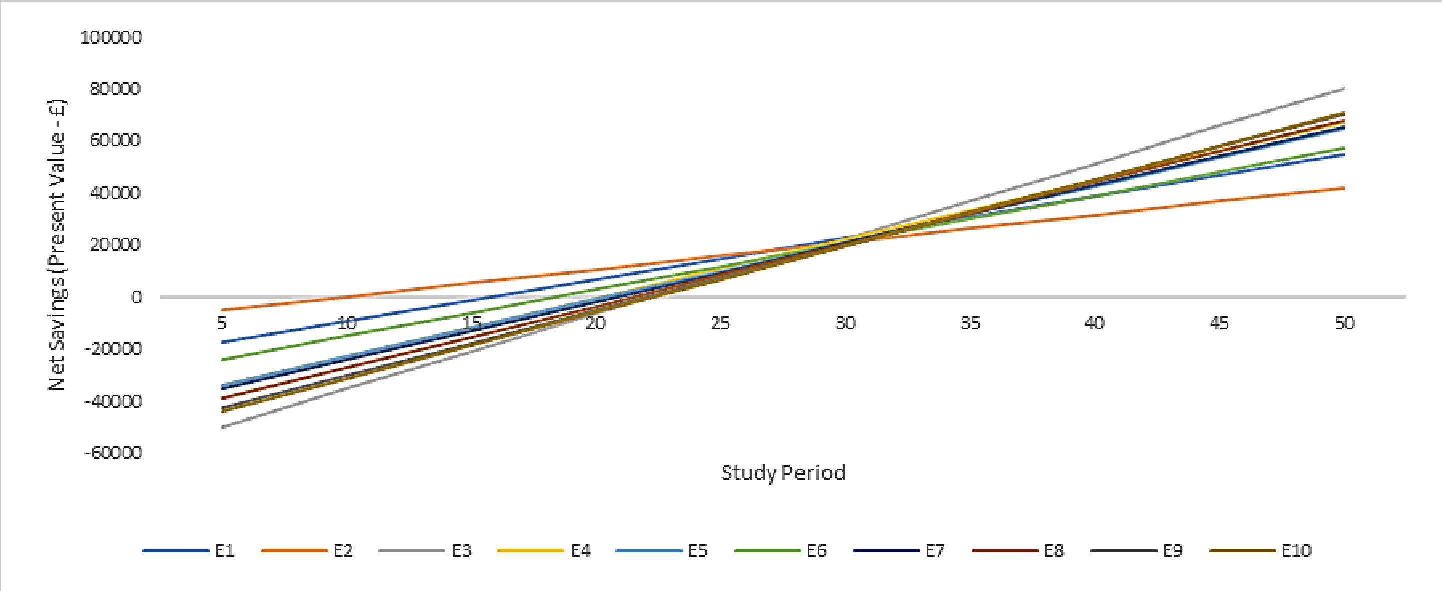


Figure 4. 7: Effect of varying the study period on net savings (present value - £)

4.5.3.4. Effect of Varying Weather data

The scenarios were simulated once more under future climate projections to see the effect of implementing nZEB retrofit under potentially different climatic conditions. The energy costs of the scenarios were therefore recalculated based on the new energy consumption values generated under future weather projections (assuming the initial constant fuel price). The future weather projections investigated are the 'High' scenarios for the 2020s, 2050s, and 2080s weather data sets. Interestingly, Figure 4.8 shows a decline in net savings as future weather projections are simulated for the nZEB scenarios. Meanwhile for scenarios E1 and E2 there is a slight increase in the net savings. This is because the projections showed a continuous increase in temperatures over stipulated timelines which led to an increase in the energy consumption. The high levels of insulation and airtightness for the nZEB scenarios meant that the cooling demand increased significantly in comparison to scenarios E1 and E2 which did not include improvement to the building envelope and therefore were not affected in the same way as the nZEB retrofit scenarios.

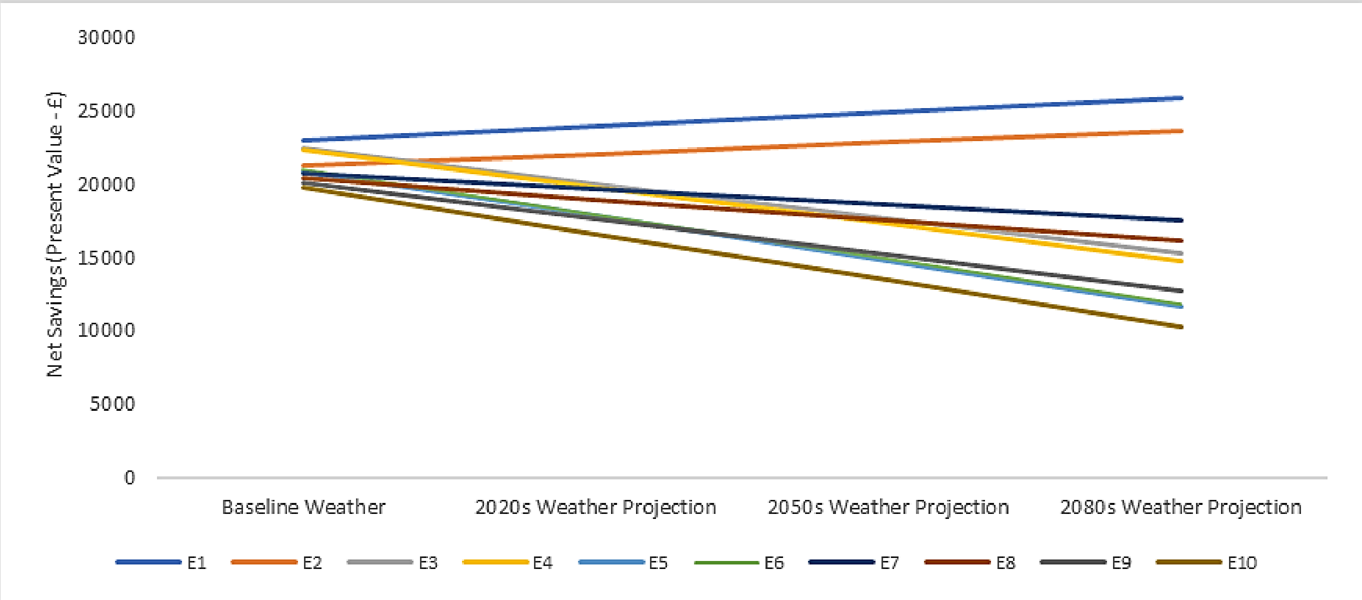


Figure 4. 8: Effect of varying the simulated weather data on net savings (present value - £)

4.5.4. Cost-Optimal Solution

To select the set of EEMs and make up the various scenarios a descriptive and iterative methodology is adopted. The results obtained provided valuable insight regarding which measures are the most cost-effective relative to their contribution. The following deductions can be obtained from the sets of EEMs above:

Rather than simply increasing the thickness of insulation materials an optimal thickness needs to be determined and selected. This can be seen by looking at the U-values for scenarios E6-E10, which use the same material but had an increase in thickness. This showed that increasing the thickness of material past a certain thickness provided little/no decrease in U-values. Furthermore, based on the sensitivity analysis results, improving the building envelope should be carefully selected to ensure that under future climate change the building can maintain its near-zero status.

In terms of cost effectiveness, the solar thermal heating system and high efficiency biomass boilers are the most cost effective at meeting heating and DHW demand whilst having lower initial investment costs and benefiting from their eligibility for the RHI and FIT schemes which further lowers the LCCs. Although Ground/Air source heat pumps are eligible for the RHI scheme, their very high initial investment costs, and the lower efficiency, in comparison to the other two measures, mean the investment cost is not justified.

To meet all/most of the electricity demand a 4kW PV system is the most suitable option and will allow the nZEB standard to be reached even if other elements are neglected. This will further lower the initial costs. Similarly, the 2kW micro-CHP system can meet and even exceed the annual electricity demand of the dwelling. Furthermore, the CHP system also has the benefit of supplying heat and can meet most of the DHW demand. Nonetheless, it should be noted that, as nZEBs are intended to be truly energy efficient buildings. Therefore, rather than just meeting the near-zero balance, it is important that the energy efficiency of the dwelling overall is improved to lower the demand of the dwelling as opposed to introducing a large renewable system to meet the existing high demand.

Financially, it is more effective to select double glazing (with a low emissivity coating) rather than triple glazing. Although scenarios with double glazing did not meet the nZEB target for window u-values, overall, the space heating demand, energy consumption, and carbon emissions did not vary. Instead, sets with double glazing had lower initial investment costs, total LCCs and shorter payback periods thereby leading to higher investment.

Mechanical ventilation systems increased investment and LCCs under current and future weather projections. Overall, they contributed very little to the overall energy and cost-efficiency of the dwelling. Adequate insulation combined with natural ventilation performed more effectively under future weather projections. Combining a medium level approach for insulation and glazing means that passive ventilation can be used as the air quality will not be affected. It should be noted however that this is only applicable to houses due to the amount of natural ventilation that can be achieved form opening of windows. In a single aspect apartment, this would not be sufficient.

As discussed previously, the directive has proposed that the cost-optimal solution is selected based on the comparison of the LCCs of the different combinations of scenarios to the PEC of the dwelling (kWh/m^2/yr). However, prior to comparing the PEC with the LCCs, the nZEB scenarios are altered according to the findings above and their LCCs recalculated. The alterations are as follows:

- The insulation of scenarios E3-E10 will be changed so that the external wall is 130 mm EPS, the Roof and Ground floor are 95 mm and 80 mm XPS, respectively. Any further increase in thickness increases costs unnecessarily.
- Natural ventilation will be simulated for all scenarios
- Measures which used Ground/Air source heat pumps will be altered so that they use a high efficiency gas boiler.
- All glazing for scenarios E3-10 will be changed to 'Double Glazing, Argon Filled, Low-e.'

The altered scenarios are now labelled AE3-AE10. The LCCs and primary energy demand of scenarios E0-E10 plus scenarios AE3-AE10 were used to make up the cost-optimal range shown in Figure 4.9. The previous LCC calculations showed that solution E3 is the cost-optimal solution. Correspondingly, the altered solutions also demonstrate that scenario AE3 is the cost-optimal solution as it is the lowest point on the cost-optimal curve. The percentage decrease in investment cost and LCCs between solution E3 and AE3 is 39.12% and 32%, respectively. In general, the altered solutions showed a 35-45 percent decrease in cost in comparison to the initial scenarios. Whilst this altered solution does not meet all the different targets (e.g. u-values) outlined earlier, the energy consumption and carbon emissions did not exceed the nZEB goal. Based on this it can also be seen that the cost-optimal level for the retrofit of a typical UK residential dwelling is 75.5kWh/m^2/yr; meanwhile, the UK's current nZEB target stands at 44kWh/m^2/ yr. Meaning there is a gap between the current nZEB target and the established cost-optimal level. One of the simplest ways to bridge this gap would be to improve the rates for the currently available incentive schemes and possibly introduce new ones to further support the economic feasibility of the nZEB standard.

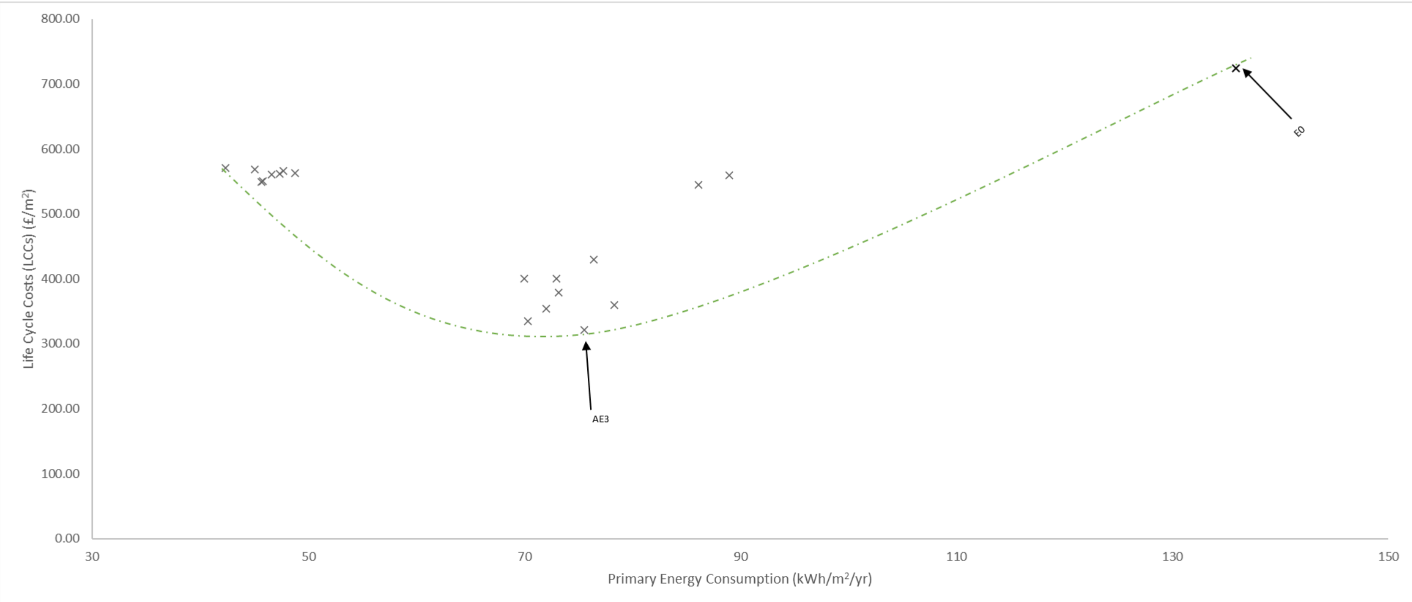


Figure 4. 9: Life cycle costs against primary energy consumption for all the retrofit scenarios

4.6. Summary and Conclusions

This section explored a LCCA of various energy efficient, nZEB retrofit scenarios on a typical UK house. Areas of focus to retrofit the dwelling were categorised based on a descriptive methodology. A parametric optimisation utility within Tas software is adopted to select the sets of retrofit scenarios.

The general trends observed is that to successfully retrofit an existing building of typical stock, with poor energy performance, several measures must be implemented. This is demonstrated by the results obtained from the analysis of individual measures. Even when a solar panel is introduced on its own, the building's performance is not that of a nZEB. Whilst it is essential that several measures are incorporated to ensure the building reaches the standard. The number and type of measures needed will depend on the original/ baseline energy performance of the building being retrofitted. This is because certain buildings will inevitably be more challenging to retrofit due to their very poor initial energy performance and building material in comparison to others. Meaning that they will need more measures to reach the energy performance standard required.

As expected, there is a progressive increase in the energy consumption and carbon emissions of the dwelling as the final model is simulated under the various timeline scenarios. Currently, most energy consumption is a result of heating demand, which is expected due to the UK's cold dominant climate. As future projections estimate an increase in temperatures it is plausible that there will be a shift from high heating demand to high cooling demand. However, the simulation results showed that the heating demand remains high and only decreases by less than 24%; meanwhile, the cooling demand increases by more than 80% between the baseline model and 2080s timeline. However, it should be noted that as the worst-case projections were used, the weather scenarios may not present an accurate reflection of the true weather conditions in coming years. The three future timeline scenarios examined also demonstrate that in coming years it may be inevitable that many buildings will need a cooling system. Even though the case-study model had mechanical ventilation the cooling demand increased significantly and eventually the building is performing below the definition's standard. A possible solution which would achieve maximum occupant comfort would be incorporating an automated shading system.

The following general conclusions can be made about reaching the standard with a focus on cost efficiency, firstly, the building to be retrofitted should be analysed, and its base performance determined to establish areas of focus. Based on this, the next step should be to select the appropriate retrofit scenarios with EEMs applicable to the dwelling. Once this is done the energy performance, including the PEC, of the dwelling for each scenario may then be checked for compliance with selected standard. Subsequently, the economic calculations for each retrofit scenario may then be carried out for the selected study period. The cost-optimal solution may then be selected based on a balance between nZEB targets and the LCCs of the retrofit measures.

The results highlighted that incorporating a renewable/trigeneration system is crucial to achieving the Near-Zero standard. Even with triple glazing and very high levels of insulation the energy consumption and carbon emissions levels would not meet the nZEB standard when simulation trials were being conducted initially. Moreover, incorporating renewables did not have a significant impact on overall cost-effectiveness as illustrated by the lack of difference of the LCCs between scenarios E1 and E2 and the nZEB scenarios.

For this investigation it was decided that the most cost-effective solution is the nZEB solution with the lowest LCCs and therefore highest net savings, which is scenario E3 and finally the altered scenario AE3. Scenarios E1 and E2 showed that it is possible to improve the energy efficiency of the dwelling with very low initial investment costs (less than £70/m^2) and still generate net savings. The results showed that with the current prices of EEMs, retrofitting dwellings to reach the nZEB standard may mean the initial investment costs are higher than certain landlords' budget capacity. Therefore, from this point of view it may be more realistic to improve the energy efficiency of the dwelling to some extent now by 40-50 percent, as in the case of scenarios E1 and E2, then as EEMs' application becomes more widespread, leading to lower costs, they can be incorporated in the future.

Retrofitting to improve the building fabric increased the overall investment costs significantly; meanwhile, their contribution to reducing energy consumption and carbon emissions were insignificant in comparison to some of the renewable measures which had similar initial costs. Moreover, the energy consumption and carbon emissions targets were achieved when the building fabric measures were not improved for the altered scenarios. However, this does not mean they should be entirely neglected; as an alternative, building fabric material should be carefully sized and selected to reasonably improve overall u-values whilst keeping costs to a minimum. This also emphasises that to successfully retrofit existing buildings, it will be necessary to redefine the energy performance level of the building fabric to match a realistic cost-effective level, that will also consider the requirements of the investor.

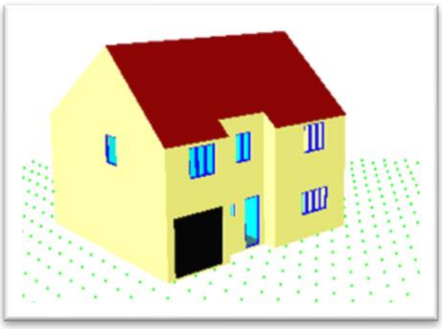
The purpose of conducting the sensitivity analysis is not only to investigate the influence of various fluctuating variables and analyse which of those variables have the greatest impact on net savings, but to also examine under which conditions do the nZEB retrofit scenarios increase in cost-effectiveness. The sensitivity analysis therefore showed that the 'ideal' combination of a discount rate $\leq 3\%$, an increase in fuel price $\geq 5\%$, and a longer ($\geq 30\ years$) calculation/ investment period considered will mean the nZEB retrofit scenarios become more cost-effective for the homeowner. It is interesting to observe that the nZEB retrofit scenarios decreased in cost efficiency as future weather projections were simulated. To counteract this issue, two options are available, one would be to include an energy efficient cooling system as part of the retrofit. On the other hand, the other option would be to exercise cautiousness when improving the building fabric to avoid any overheating because of raised temperatures in the future. Generally, this illustrates the importance of careful planning and designing to retrofit a resilient building that performs up to standard even under potentially different climatic conditions.

Overall, the cost-optimal solution that was selected was based on net savings over the calculated study period. In real life applications, the cost-optimal solution will largely depend upon the requirements of the investor. However, the same steps of creating several retrofit scenarios and comparing them is essential to reaching the nZEB standard with cost-optimal levels.

4.7. Case Study 2

4.7.1. Building Description

Seven different residential properties are examined in this section. Properties 'A3-A7' are all located in the London Borough of Hillingdon (the westernmost of the London borough councils) (Figure 4.10). Meanwhile properties 'A1-A2' are located Bracknell, Berkshire, England. The properties were selected based on several criteria: design, build year, location, and occupant availability. Properties 'A3-A7' are built in the period 1929 to 1939 and the other two properties are built post-1930s but pre-1990s. The properties cover all types of houses available in the UK. Only 14% of the UK population currently live in a flat or maisonette; although it should be noted that within London 43% of Londoners live in a flat. Nonetheless, the properties are highly representative of the UK typical housing stock. The home-owner(s) were all willing to be interviewed. They provided details of their daily activities, such as their preferred heating set points, window opening schedule etc. so that the impact occupant behaviour has on energy consumption can be studied to assess the extent to which it is potentially a contributing factor to the energy performance gap. The seven properties were specifically selected to represent all types of available residential houses in the UK. It is important to include more than one case study for this investigation to gain an accurate insight into which factors affect the performance gap and to what extent their influence can be on this. Furthermore, it will be very interesting to compare the initial energy consumption of houses with a similar size and occupancy rate. Table 4.11 is showing a summary of the details for the various houses and Table 4.11.1 is showing a summary for the heating and window opening schedule.



A1

A2

A3

A4

A5

A6

A7

Figure 4. 10: Tas 3D modelling results of all dwellings

Table 4. 11: Summary of characteristics for all dwellings

		Typical block characteristics						
Element/System		**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**
Type		Detached	Semi-detached	Terraced	Detached	End of terrace	Mid-terrace	End of terrace
Building fabric	***Type***	Solid wall; original build; cavity wall	Solid wall; original build; cavity wall	Solid wall; original build; cavity wall	Solid wall	Solid wall; original build; cavity wall	Solid wall	Solid wall; original build; cavity wall
Total No. of occupants		4	2	3	1	2	3	1
Wall (calculated area weighted average u-values)	***u-value (W/m^2K)***	0.32	0.35	0.33	0.30	0.32	0.35	0.32
Roof (calculated area weighted average u-values)	***Type***	Gable roof	Pyramid hip roof	Gable roof	Gable roof & shed roof	Gable/hip roof	Saltbox/gable roof	Hip roof
	u-value (W/m^2K)	0.30	0.30	0.31	0.33	0.32	0.31	0.30
Floor (calculated area weighted average u-values)	***Type***	Concrete	Concrete	Timber	Concrete	Timber	Timber	Concrete
	u-value (W/m^2K)	0.57	0.54	0.57	0.65	0.54	0.60	0.57
Windows (calculated area weighted average u-values)	***Type***	Double glazing (air-filled)	Double glazing (air-filled)	Double glazing (air-filled)	Double glazing (air-filled)	Double glazing (air-filled)	Double glazing (air-filled)	Double glazing (air-filled)
	u-value (W/m^2K)	2.80	2.80	2.90	2.45	2.45	2.95	2.80
Cooling		No cooling system						
Heating	***Fuel***	Natural Gas						
	Temperature Set Point	19°C	17 °C	16 °C	18 °C	21 °C	22 °C	20 °C
	Heating Capacity	2-3 kW						
	Working temperature	60-80°C						
	Heating distribution	Central heating radiators						
	Schedule	20:00-6:00	23:00-7:00	23:00-5:00	23:30-3:00	18:30-5:00	17:00-6:00	21:00-5:30
Domestic Hot Water (DHW)	***Type***	Conventional gas boiler system	Conventional gas boiler system	Combi boiler	Conventional gas boiler system	Combi boiler	Conventional gas boiler system	Conventional gas boiler system
	Temperature	45-52°C						
	Average daily consumption	130-140 litres per person per day						
Ventilation	***Type***	Passive/Natural						
	Schedule	8:30-18:00	8:00-15:30	13:00-15:00	12:00-14:30	8:00-16:00	14:00-17:00	17:30-19:00
Zone - occupancy levels, people density, lux level	***NCM constructions database -v5.2.tcd***	Bedroom - 0.094 person/m², 100 lux Toilet - 0.1188 person/m², 200 lux Reception - 0.105 person/m², 200 lux Hall - 0.183 person/m², 300 lux Food prep/ kitchen- 0.108 person/m², 500 lux Eat/Drink area - 0.2 person/m², 150 lux Circulation - 0.115 person/m², 100 lux Store- 0.11 person/m², 50 lux Laundry - 0.12 person/m², 300 lux						
Air permeability		5-10 m³/h/m² @50Pa						
Infiltration		0.500 ACH						
Lighting Efficiency		5.2 W/m² per 100 lux						
Fuel Source		Natural Gas – CO_2 Factor – 0.216 Kg/kWh						
		Grid Electricity – CO_2 Factor – 0.519 Kg/kWh						
Weather data		DSY (Cibse) for London. Includes: dry bulb temperature (°C); wet bulb temperature (°C); atmospheric pressure (hPa); global solar irradiation (W·h/m²); diffuse solar irradiation (W·h/m²); cloud cover (oktas); wind speed (knots); wind direction (degrees clockwise from North); and Present Weather Code.						

[1] refers to brickwork and blockwork constructions (walling is of masonry construction and tied with stainless steel ties to an outer leaf of block/brick)

4.7.2. Baseline Model validation

Figure 4.11 is showing a comparison of the modelled energy consumption versus the actual energy consumption (as obtained from energy bills). Despite certain houses being comparable in size and the number of occupants, their energy consumption varies greatly. This difference can be attributed to occupant behaviour: For instance, the 2 occupiers of house A3 maintain a set internal temperature of 16°C most of the year. This comfort level might be at the low end for many people, but the outcome can be seen directly in terms of the yearly energy consumption. On the other hand, for the 2 occupiers of house A6, the opposite scenario holds true; their usual temperature setting is around 22°C, which is equally reflected in the annual energy consumption. It is interesting to observe that this 3°C between house A6 and A1 led to a difference of less than 1440 kWh or 4% difference in their annual energy consumption. Meanwhile, the 6°C between difference between house A3 and A6 led to an astonishing 55% difference in their annual energy consumption (based on actual energy consumption comparison). In terms of the percentage difference all the houses had a difference within the range of 27% to 32%, with 27% being the most common gap. This corroborates the idea within the literature that there may be common factors which lead to this performance gap between actual and simulated energy consumption. In other words, there are certain (potentially behavioural) factors which Tas does not account for this, thereby, leading to this difference.

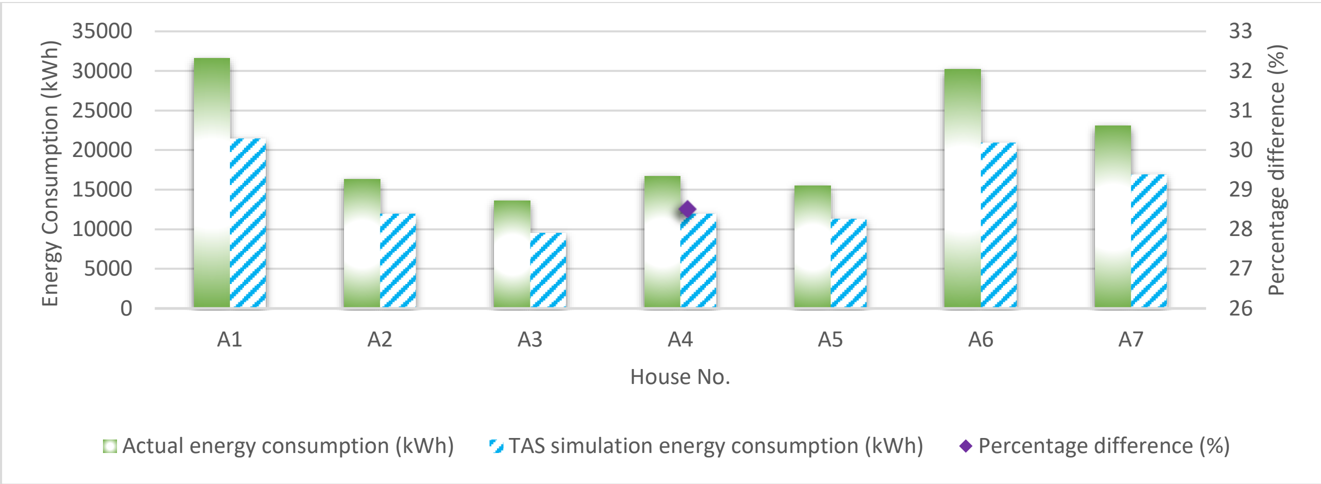


Figure 4. 11: Comparison of the modelled energy consumption versus the actual energy consumption and the percentage difference

4.7.3. Factors That Affect the Performance Gap

The above highlights the extent to which occupants can affect energy consumption due to differences such as the heating set point. To investigate this further three factors have been selected, namely, the heating set point, heating schedule, and window opening schedule. These have been selected as they are the specific factors that have been documented in the literature to potentially influence energy consumption. For this work it is not possible to investigate or monitor how often lighting and appliances are being used, due to the monitoring equipment (such as plug load meters) and time scale required to provide reliable and realistic results. The usage of DHW is not investigated as this is largely influenced by the number of occupants in a dwelling, therefore, a larger study is required to provide tangible results that can be compared and verified. For each of the factors selected the set parameter is that the set point or schedule will be increased by 4 ^{o}C or 4 hours, and this will be done by 1^{o}C or 1-hour increments on Tas. The effect of the '1 point' increase on energy consumption is examined and the percentage difference between this and the actual energy consumption is compared. Table 4.12 is showing the summary of the factors may contribute to the performance gap and are investigated in this section.

Table 4. 12: Summary of factors investigated for contributing to the performance gap

Factor	Unit	Parameter
1. Heating set point	^{o}C	+4 ^{o}C from current set point
2. Heating schedule	Hrs/day	+4 hours from current schedule
3. Window opening schedule	Hrs/day	+4 hours from current schedule

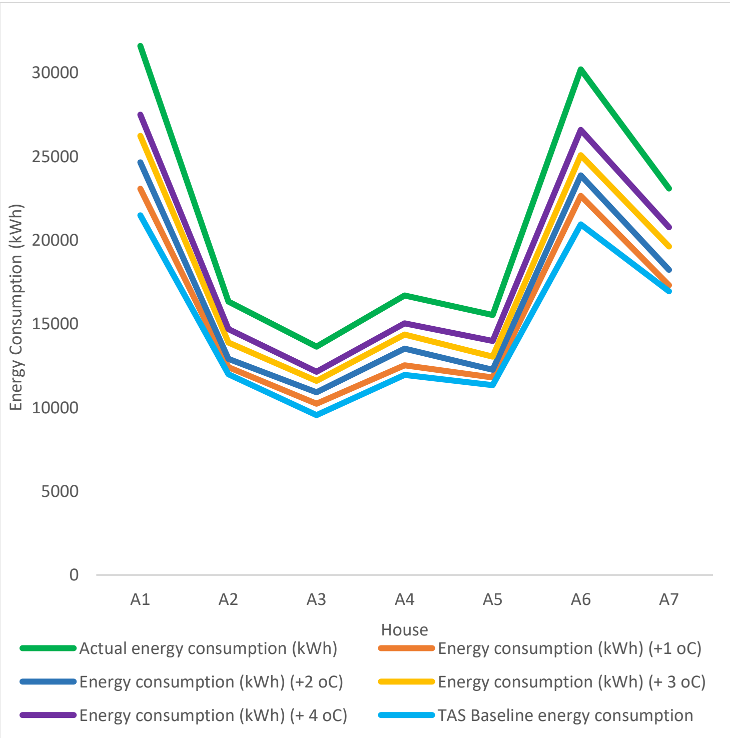
Figures 4.12a, b, and c are showing the actual energy consumption against the Tas energy consumption for the various altered factors. Looking at Figure 4.12, it can be seen that for all the factors investigated, as the behaviour is increased from the 'real-life' point or schedule on Tas, the performance gap is decreased. This potentially means that Tas and other simulation software underestimate the effect activities such as heating set point and schedule have on energy consumption. An alternative explanation is that although occupants have provided details of their 'typical' heating set point or schedule this does not mean it is followed faithfully in the same way that the software would project. For example, factors such as thermal comfort play a significant role in occupant behaviour. Even if an occupant knows that in general, they keep their house at a set temperature, on a particularly cold day or week or several weeks this 'typical' behavioural pattern will change without much thought. Whilst this will be reflected in the operational energy use, it cannot be translated to the software. The same can be said during a heatwave and the effect it has on window opening schedule.

For the altered heating set point, the results show that an increase of 1^{o}C leads to a 5% improvement in the performance gap between actual and simulated energy consumption for house A1. Meanwhile, a 4 ^{o}C increase leads to a 19% improvement. In other words, the performance gap between simulated and actual energy consumption for house A1 after a 4 ^{o}C increase in the heating set point decreased from 32% to 13%. A similar trend is observed for all houses. The percentage decrease for all the houses with the heating set point +4 ^{o}C is in the range of 10%-13%. Between the baseline Tas simulation and this simulation there is a 22% improvement for house A1 and an average 20% for all houses. Although this 10%-13% represents an underestimation of the actual average energy consumption, the accuracy of the simulation will always depend on factors which cannot be fully replicated such as the weather data amongst other points discussed above. However, what this suggests is that the heating set point plays a significant role in affecting the energy consumption within Tas software.

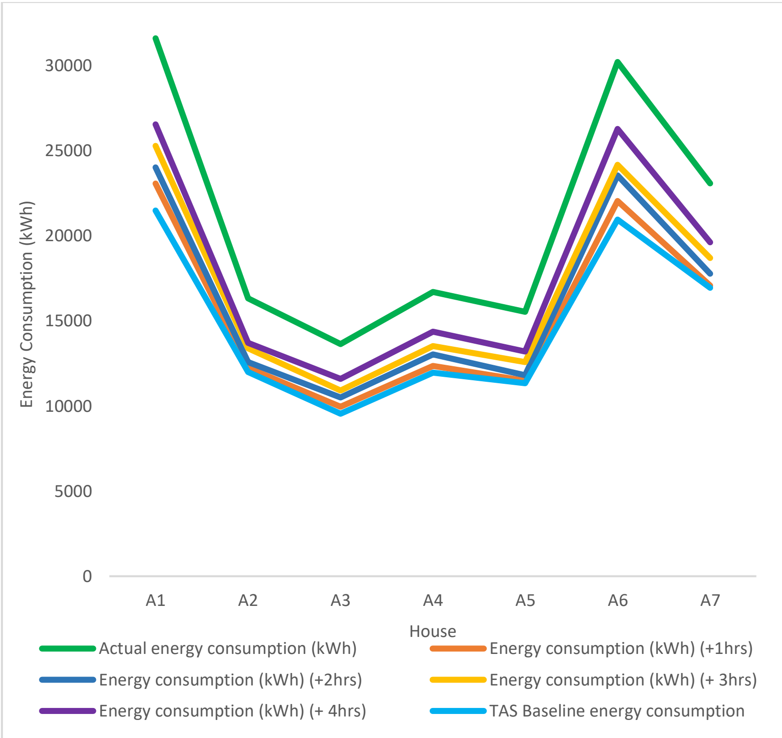
Looking at the results with the altered heating schedule, it can be seen that the effect this has on decreasing the performance gap is less than the effect of altering the heating set point. For example, once again looking at house A1 an increase of 1hr leads to an identical 5% improvement in the performance gap between actual and simulated energy consumption for the house. Yet the 4hrs increase leads to a 16% improvement. The percentage decrease for all the houses with the heating schedule +4hrs is in the range of 13%-16%. Between the baseline Tas simulation and this simulation there is a 19% improvement for house A1 and an average 17% for all houses.

Finally, looking at the effect the window opening schedule has on the simulated energy consumption, there is a larger gap between the actual and simulated consumption, as shown in Figure 4.12c. For house A1 an increase of 1hr leads to a 3% improvement in the performance gap between actual and simulated energy consumption for the house. Between the baseline Tas simulation and this simulation there is 16% improvement for house A1 and an average 15% for all houses. The 4hrs increase leads to a 13% improvement from the baseline performance gap (i.e. a 19% percentage gap). This 19% gap is significantly higher than the 10% and 13% average experienced with the altered heating set point and heating schedule, respectively. Nonetheless, even something as simple as changing the window opening schedule had a reasonable effect on the performance gap and improved the simulation results by 16%.

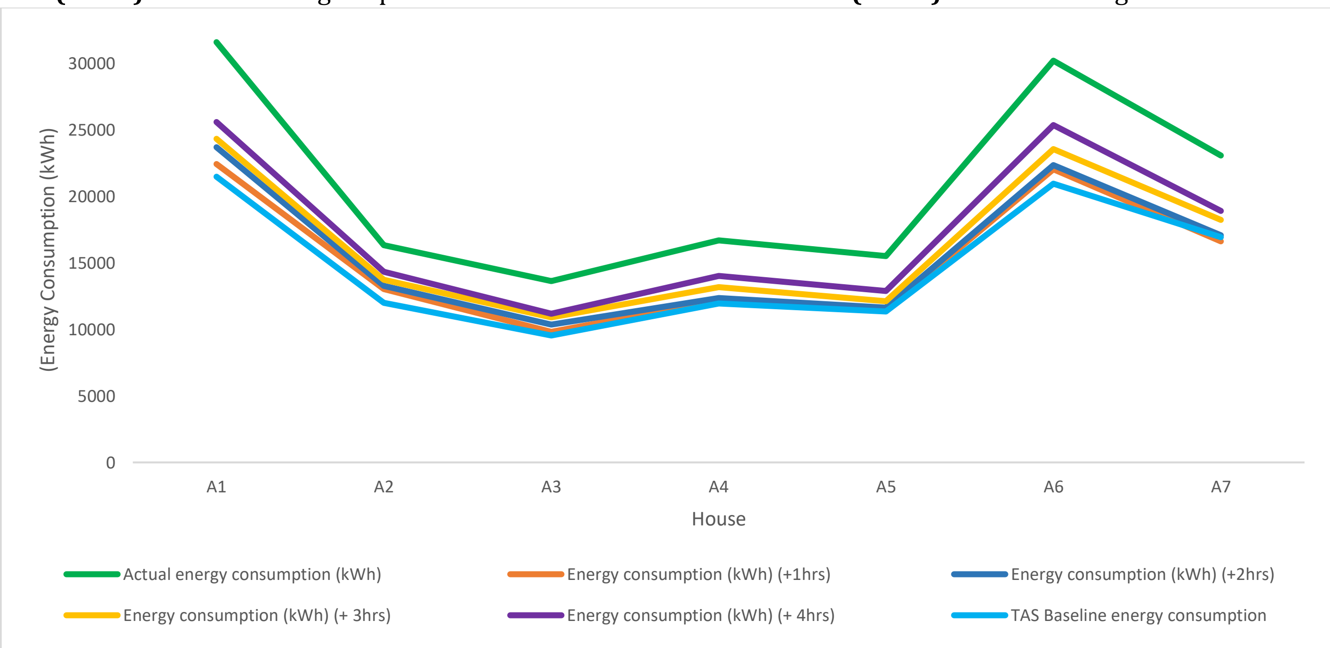
In general, the results are in consonance to other findings in the literature that state that the influence of occupant behaviour on the total energy consumption is significant. The knowledge of the results can be used to educate occupants on the impacts of their behaviour on the total energy consumption and how they can actively help in reducing their energy usage.



(4.12a) altered heating set point



(4.12b) altered heating schedule



(4.12c) altered window opening schedule

Figure 4. 12: Actual versus Tas simulation energy consumption and percentage difference with (a) altered heating set point (b) altered heating schedule and (c) altered window opening schedule

4.7.4. Summary and Conclusions

Bridging the energy performance gap is vital in ensuring that a designed or retrofitted building meets the energy performance targets that are set at the beginning of the project. This section presented a simulation model of seven different residential UK buildings. The model is initially simulated to replicate the current state of the buildings and the self-reported occupant behaviour such as the window opening schedules and thermostat setpoint temperature and schedule to see what the impact on energy consumption due to different occupants' behaviours can be. The results from the various models are validated by comparing the actual energy consumption (as obtained from energy bills) with the simulated.

The simulation results showed that the heating set point has the greatest impact on the simulated energy consumption out of the other investigated factors. The results also demonstrate that the energy consumption of the dwellings can be significantly reduced by appropriately applying window opening schemes and by controlling the heating setpoint temperature and schedule. Keeping windows closed in winter and allowing solar radiation to be transmitted through them helps to reduce the heating loads of the house.

Although the investigated factors attempt to account for the reasons behind the performance gap, it is demonstrated that a direct comparison of predicted versus measured annual energy use is difficult. This is largely caused by uncertainties in the available data that are very difficult to model and propagate in energy simulations. For example, the self-reported data, whilst it can be considered a modest representation of an occupant's behaviour, it will never be able to wholly replicate it. Furthermore, plug loads can also play a significant role in affecting the energy consumption and this is something that could not be studied for this work but would need further investigation to see the full impact plug loads have on total energy consumption.

A coordinated approach is needed to better understand, and eventually bridge, the energy performance gap. Additional gathering of data that represents deep insights into occupant behaviour through both robust monitoring work (i.e. exact actual daily energy use of occupants) and improving the forecasting of long-term weather projections etc. Finally, it must be noted that the energy consumption is only one performance aspect of a building's performance. Once predicted and actual energy use are matched, further work will be needed to address performance gaps in areas such as thermal comfort and indoor air quality.

4.8. Case Study 3

4.8.1. Building Description

The final analysed residential case study is Hughenden Gardens, located in High Wycombe. It is made up of 7 blocks (A-H) as shown in Figure 4.13a and Figure 4.13b. Table 4.13 is showing a summary of the building characteristics details and outcome of the modelling process. Flats within the village have an average of 2 occupants per dwelling. Flat occupancy type is split into 70% residential occupancy and 30% nursing occupancy.

Homes within the retirement village share common characteristics, and therefore issues. As discussed earlier behavioural changes are not always an applicable solution. This is especially true for this type of housing due to the prototypical demographic of occupants who are classed as part of the susceptible population to overheating. In tandem with this, the risk of overheating as a potential threat is exacerbated as it can lead to preventable loss of life.

The selected weather file is the London Probabilistic Design Summer Year (DSY) [WDD16LON]. This is selected because the DSY weather file is suitable for overheating analysis. Meanwhile, the Test Reference Year (TRY) is suitable for "energy analysis and compliance with the UK Building Regulations (Part L)" [Cibse, 2009a; Eames, Ramallo-G, and Wood 2016; Mylona 2017; Cibse 2017].

The database closest in terms of geography to the retirement village is the westernmost of the three London regions: London Heathrow. Cities tend to be warmer than rural districts around them, most noticeably during the night hours, and this difference in temperature is accounted for in the data (Cibse, 2017). Known as the urban heat island (UHI) effect, the Cibse data uses a larger number of weather stations within each region to monitor temperature more closely. Future climate change is also taken into consideration.

The four-time periods selected were as follows: a baseline for the present era, together with the 2050s, and 2080s DSY. The databases are as follows: the 'High' emissions scenario, 50th percentile which features short intense warm summer temperatures (DSY 2). DSY 1 is comprised of a moderately warm summer, whilst DSY 3 features long, intense warm spells. Currently, DSY 1, 50th percentile is recommended by the Cibse TM59 criteria for carrying out the overheating analysis and is therefore selected.

The buildings within the retirement village are designed to reach the nZEB standard with the currently recommended overheating mitigating strategies as obtained from the literature. Furthermore, because in overheating studies there is currently limited research regarding whether combined cooling/ heat and power (C/CHP) systems have the potential to act as mitigating strategies to reduce the risk of overheating they will be investigated. Consequently, the risk of overheating and energy performance of the various blocks within the retirement village as they currently stand and as nZEBs is investigated under current and future climatic conditions. The analysis is carried out using Tas). The overheating criteria selected is the CIBSE TM59 Design methodology for the assessment of overheating risk in homes.

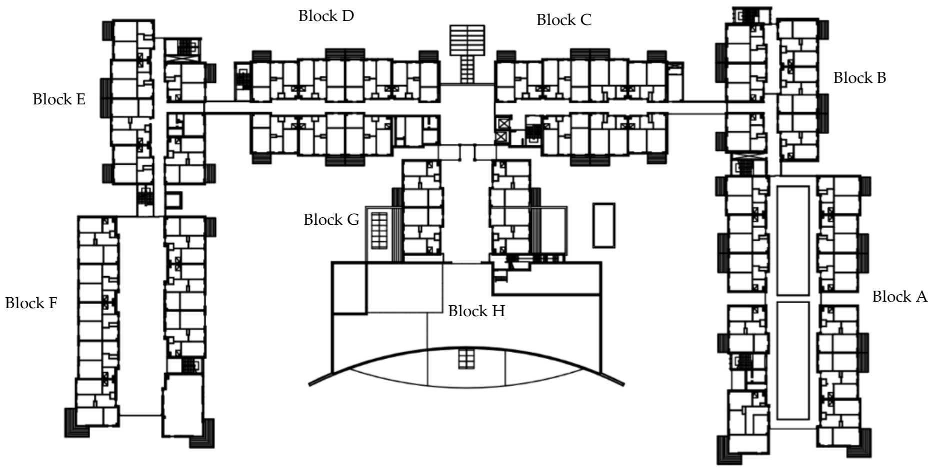


Figure 4.13a: Typical floor plan of the retirement village

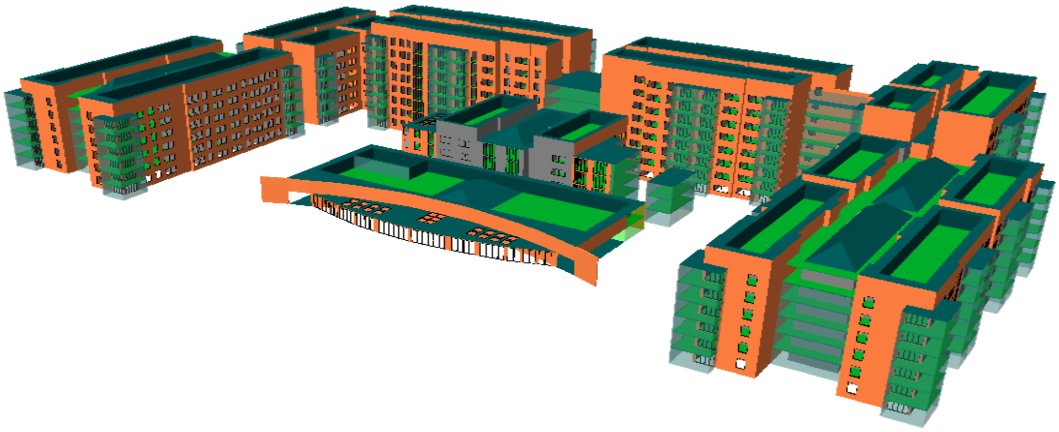


Figure 4.13b: 3D model of the retirement village

Figure 4. 13: (a) Floor plan and (b) 3D model of the retirement village

Table 4. 13: Summary of building characteristics

		Typical block characteristics		
Element/System		**A, F & G**	**B-E**	**H (Village centre)**
Use		Residential & nursing occupancy	Residential & nursing occupancy	Leisure centre, gym, communal area
Building fabric	***Type***	Traditional build[1] including block, bricks, and precast units (stair-case and slabs)	Mixture of concrete frames & traditional build	Concrete frame, steel frames (mainly iterance) and blocks and bricks
Total No. of flats		260 [105 one bedroom; 155 two bedrooms]		
Wall (calculated area weighted average u-values)	***u-value (W/m²K)***	0.45		
Roof (calculated area weighted average u-values)	***Type***	Single-Ply Membrane		
	u-value (W/m²K)	0.30		
Floor (calculated area weighted average u-values)	***Type***	Ground & first floor: cast concrete slab Other floors: precast slab		
	u-value (W/m²K)	0.35		
Windows (calculated area weighted average u-values)	***Type***	Double glazing (air-filled) with low emissivity coating		
	u-value (W/m²K)	2.45		
Cooling		No cooling system		
Heating	***Type***	Conventional communal boiler system		
	Fuel	Natural Gas		
	Temperature Set Point	21°C		
	Heating Capacity	3 kW		
	Working temperature	60-80°C		
	Heating distribution	Central heating radiators		
	Schedule	October-April; 10pm-8am		

Domestic Hot Water (DHW)	***Type***	Conventional communal boiler system
	Temperature	49°C
	Average daily consumption	140 litres per person per day
Ventilation	***Type***	Passive/Natural
	Schedule	8am-10am; 4-6pm
Zone - occupancy levels, people density, lux level	***NCM constructions database - v5.2.tcd***	Bedroom - 0.094 person/m², 100 lux Toilet - 0.1188 person/m², 200 lux Reception - 0.105 person/m², 200 lux Hall - 0.183 person/m², 300 lux Food prep/ kitchen- 0.108 person/m², 500 lux Eat/Drink area - 0.2 person/m², 150 lux Circulation - 0.115 person/m², 100 lux Store- 0.11 person/m², 50 lux Laundry - 0.12 person/m², 300 lux
Air permeability		5 m³/h/m² @50Pa
Infiltration		0.500 ACH
Lighting Efficiency		5.2 W/m² per 100 lux
Fuel Source		Natural Gas – CO_2 Factor – 0.216 Kg/kWh
		Grid Electricity – CO_2 Factor – 0.519 Kg/kWh
Orientation		Latitude: 51.6367/ 51°38’11” N; Longitude -0.753452°W; +0.0 UTC
Weather data		DSY (Cibse) for London. Includes: dry bulb temperature (°C); wet bulb temperature (°C); atmospheric pressure (hPa); global solar irradiation (W·h/m²); diffuse solar irradiation (W·h/m²); cloud cover (oktas); wind speed (knots); wind direction (degrees clockwise from North); and Present Weather Code.

[1] refers to brickwork and blockwork constructions (walling is of masonry construction and tied with stainless steel ties to an outer leaf of block/brick)

4.8.2. The nZEB Retrofit

The aim of this investigation is to assess how the case study building performs under current and future climatic conditions as it currently is and once it is retrofitted to the nZEB standard. Although the retirement village has communal areas it still carries a residential classification because the energy consumption, water consumption, occupancy profiles etc. are considering per dwelling. Table 4.14 is showing a summary of the selected EEMs that make up the nZEB retrofit scenario. From the currently available literature it could be predicted that nZEBs and energy efficient buildings are more likely to experience overheating. Findings from the literature suggests that the incorporation of shading devices, double glazing as opposed to triple glazing, and utilising natural ventilation are currently some of the most effective ways to mitigate the risk of overheating [Schnieder, 2009; Roaf et al. 2009; Carrilho et al. 2012; Baborska-Narożny et al. 2016].

Table 4. 14: Summary of final selected EEMs for nZEB retrofit

EEMs	Design Measure
Insulation	180mm mineral wool insulation batts
Lighting	LED [+ Auto presence detection in communal areas]
HVAC & DHW	Automatic Thermostat controlled direct gas fired Boiler
	Mechanical Ventilation with heat recovery in communal areas
Microgeneration	100kWp Solar panel system + solar thermal collectors
Overheating mitigating strategies	Internal shading
	Natural ventilation in residential areas
	Double Glazing, 36 mm Argon filled, Low-e

4.8.3. Cibse TM59 Overheating Criteria

To evaluate the impact of the measures to be incorporated on the case-study building, the initial simulation is conducted to reflect the actual current state of the building without any alterations. The simulation model is thoroughly populated to reproduce all the characteristics and systems of the building as built. Once this is completed, the retrofitting measures outlined were then incorporated and the simulations were run again with the building performing as a nZEB.

Figure 4.14 is showing the PEC for the building as it currently is and once it has been retrofitted to the nZEB standard. From Figure 4.14 it can be seen that the space heating PEC decreases for both the baseline scenario and even more so for the nZEB retrofit. However, as the nZEB retrofit incorporates mechanical ventilation in communal areas the total PEC is increased as the cooling demand substantially increases. The simulated annual PEC per dwelling is 97.48 kWh/m^2. Although the total PEC for the nZEB scenario remains lower than the baseline scenario it can still be said that the nZEB scenario underperforms in comparison to the base case. This is because the baseline scenario experienced a decrease in the total PEC, meanwhile the nZEB scenario experienced an increase in the total PEC. This suggests that if the 90th percentile/DSY 3 weather file (worst case projection) had been used for the simulations the nZEB scenario would have an even further increase in the total PEC.

Considering the typically high investment costs associated with nZEB retrofits an increase in energy usage would lead to an increase in the occupants' fuel/energy costs. Generally, with energy efficient retrofit projects the main economic appeal is the drastic lowering in energy costs. Meaning that if this is going to be reversed under hotter weather conditions the overall financial benefits and economic viability of this option would be drastically lowered.

The TM59 overheating criterion 1 and 2 results for the baseline scenario and the nZEB scenario are shown in Figure 4.15. The results are in consonance with the projected temperature changes. The projections showed a constant increase in temperature over stipulated timelines. Once the building is simulated under the 2050s and 2080s weather files the overheating hours increase significantly. The general trend observed for both the baseline scenario and nZEB retrofit across every block of the village is that kitchen and bedroom are more prone to experience severe overheating.

Although overheating occurred for both the base case and the nZEB retrofit scenario, severe overheating is experienced under the 2050s and 2080s weather projections for the nZEB scenario in comparison to the base case. For the bedroom and the kitchen, the building failed to pass the criteria under the current, 2020s-2080s weather files for the nZEB scenario. As discussed previously, several studies have confirmed that certain retrofit measures such as the implementation of shading devices, double glazing, and utilising natural/passive ventilation can act as 'mitigating' measures to significantly reduce the occurrence of overheating within buildings. Furthermore, because previous research highlights that overnight natural ventilation is supposedly one of the simplest and most effective methods to combat overheating, the openable window hours were set for 20:00pm-7am during the non-heating season. Therefore, it is of concern that despite foreseeing the potential increased risk in overheating with the nZEB retrofit and therefore including such measures, overheating is severe under future weather projections and much more prominent in comparison to the baseline scenario. In addition, flats within the village are typically dual aspect which is not always possible or common with flat type buildings. They are typically single aspect meaning they do not allow for adequate ventilation. Within the UK it is generally recommended that opening windows for approximately 15 minutes every day is enough to ventilate. However, studies have found that most properties only open windows once or twice a week which explains widespread issues of dampness across UK properties [Energuide, 2019]. Other studies (simulation and real-life) have examined daytime versus night-time ventilation and it is always concluded that night-time ventilation is the more effective option [Artmann, Manz, and Heiselberg 2007; Panayiotou et al. 2010; Campaniço et al. 2016]. Meaning that relying on passive ventilation as a mitigating strategy is not an effective solution. Furthermore, behavioural changes such as this cannot be guaranteed in real-life applications and may not be fully adhered even if residents were advised to do so and because of the particularly vulnerable population demographic this cannot be relied on as an effective or suitable method of reducing the risk of overheating for this particular case study.

External shading has been proven by the literature to be more effective than internal shading at reducing solar gains [Schnieder, 2009; Carrilho et al. 2012; Atzeri, Cappelletti and Gasparella, 2014]. However, there are issues of applicability with this particular case study. Mainly, it will be technically challenging to retrofit the façade as there may be a lack of sufficient fixing points to allow installation. This is a common challenge for existing buildings looking to incorporate external shading as part of their retrofit project. It would also greatly reduce the amount of natural light entering the space thereby affecting occupant comfort. Furthermore, the cost of running, cleaning and maintaining the external façade would incur higher maintenance costs for occupants which will not be well received by all occupants. Due to this, it is not considered a suitable mitigating strategy to be investigated. It is interesting to note that blocks B-E outperformed blocks A, F-G under the present, 2020s, 2050s and 2080s simulations. The reason for this is due to the differences in building material between the blocks. Materials with a higher thermal mass such as the precast concrete panels used in those blocks have been proven to reduce the risk overheating. However, most existing UK buildings are traditionally built (as blocks A, F, and G) meaning that the risk of uncomfortable dwellings for occupants during hotter spells will be prevalent. The fifth UK carbon budget called for solid wall dwellings to be insulated to meet the carbon reduction targets set out in the 2008 Climate Change Act. Increasing the insulation will exacerbate the risk of overheating within those dwellings. It has been predicted that approximately 2 million dwellings could be affected [CCC, 2017].

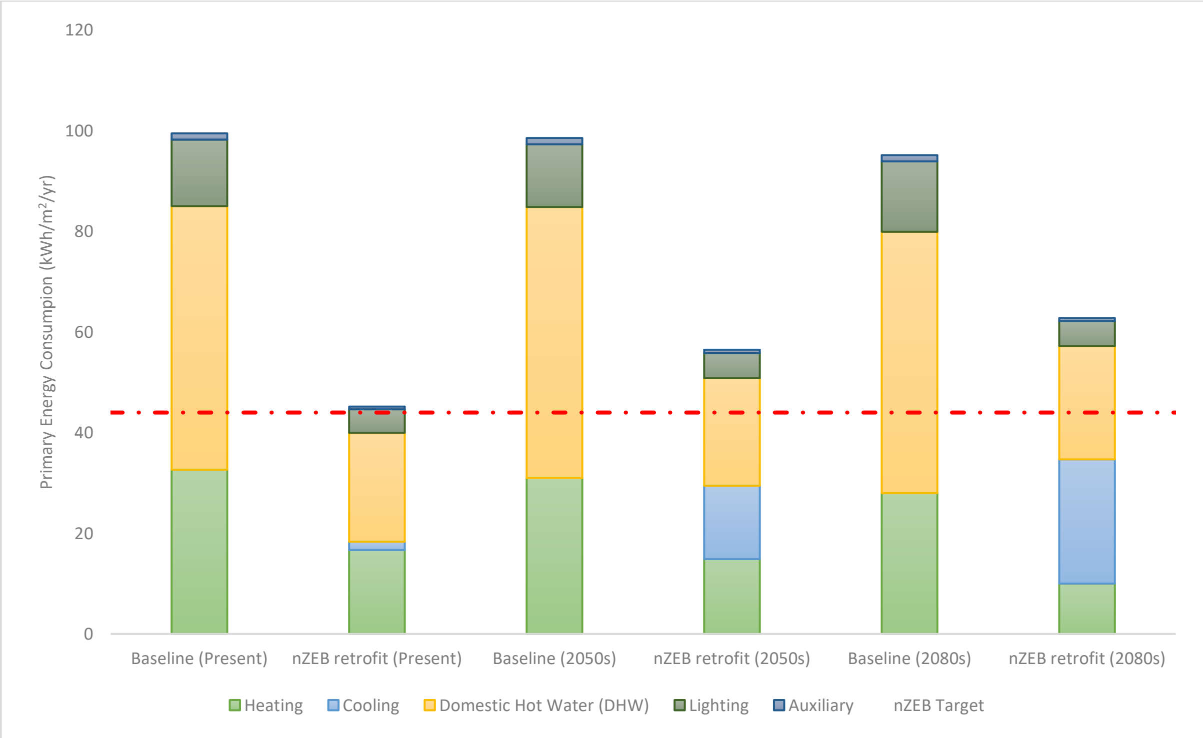


Figure 4. 14: Comparison of the primary energy consumption of the retirement village as built and after nZEB retrofit under current and future climate conditions

Figure 4.15: Cibse TM59 overheating criterion 1 results for bedroom (average)

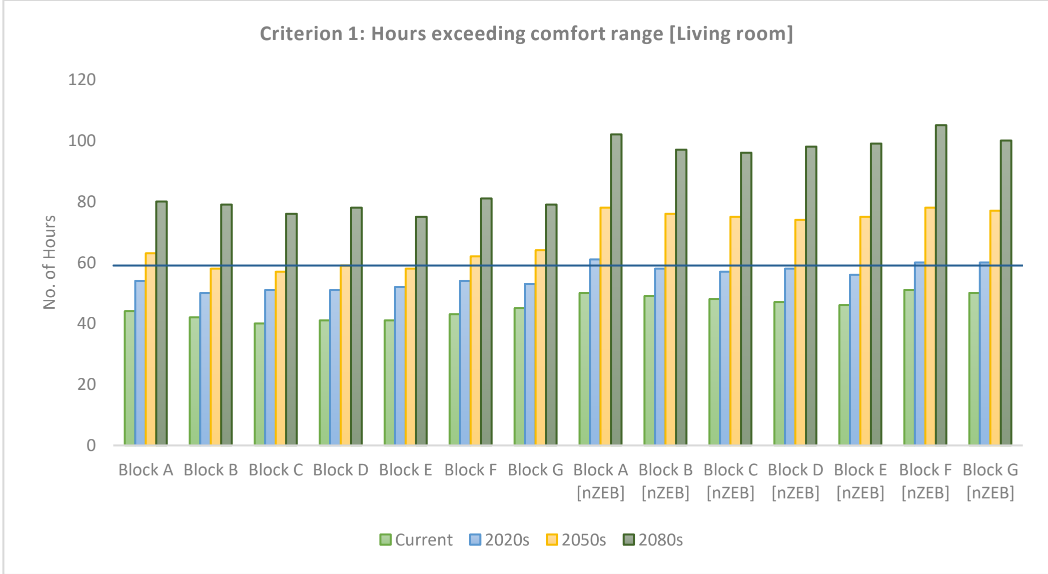


Figure 4.15b: Cibse TM59 overheating criterion 1 results for living room (average)

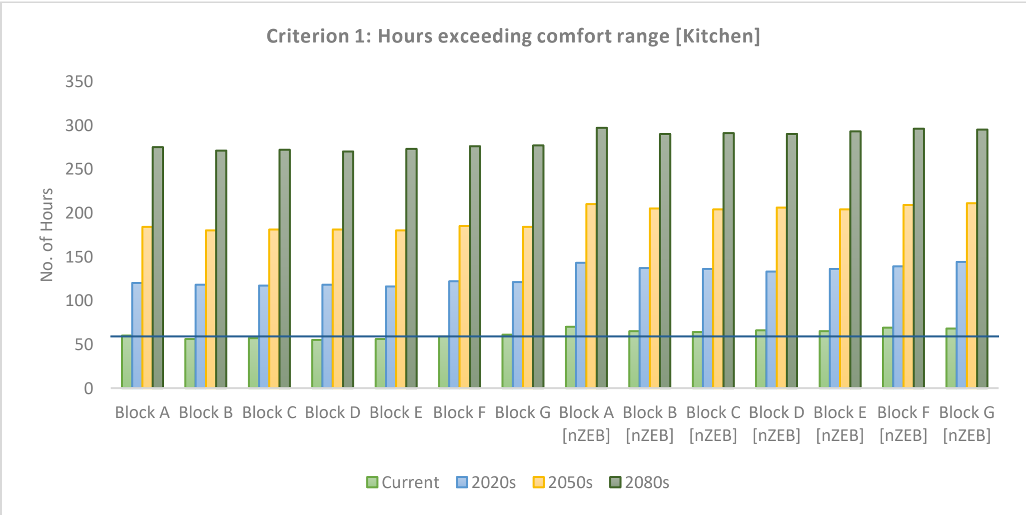


Figure 4.15c: Cibse TM59 overheating criterion 1 results for living room (average)

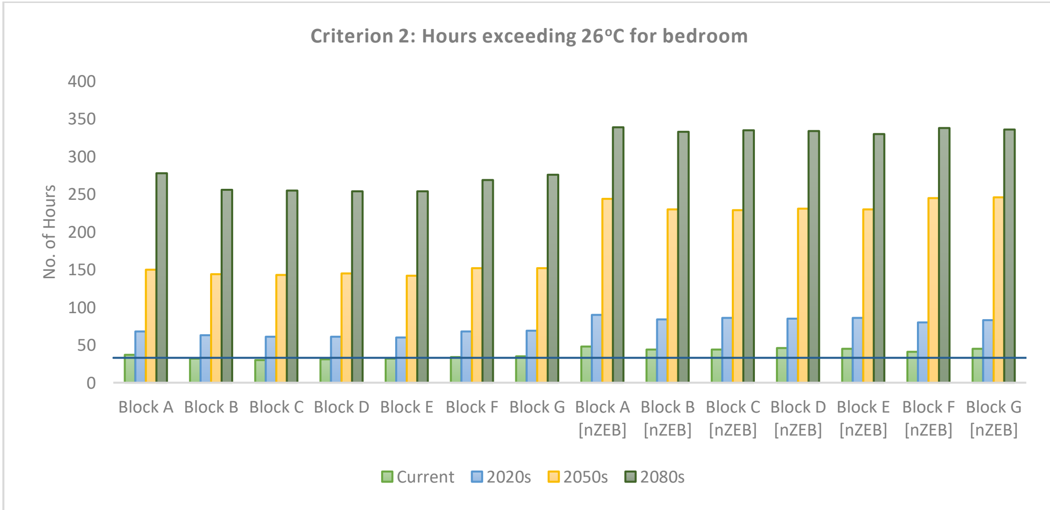


Figure 4.15d: Cibse TM59 overheating criterion 2 results for bedroom (average)

Figure 4. 15: Cibse TM59 overheating criterion 1 and 2 results for living room and bedroom (average) within the village as built and after nZEB retrofit under current and future climatic conditions

4.8.4. Mitigating Strategy: C/CHP

The previous figures suggest that the only reliable solution to avoid the risk of overheating would be to utilise some form of cooling measure throughout the entire village. The intrinsic features of existing buildings can be adapted to improve their energy performance, however, as demonstrated opening windows in this case study has not provided the level of ventilation required to avoid overheating. Currently, air conditioning is the most widely used cooling system in both commercial and domestic applications. However, this alternative is incompatible with the nZEB concept that revolves around reducing energy use and CO_2 emissions. Several studies have demonstrated the potential for combined heat and power (CHP) and combined cooling, heat, and power (CCHP) to reduce the PEC of buildings and aid in reaching the nZEB standard [Maria, Jose, and Eva 2017]. As discussed, in overheating studies there is currently limited research regarding whether C/CHP have the potential to act as a mitigating strategy to reduce the risk of overheating. Consequently, as part of the nZEB retrofit rather than incorporate the PV system and solar thermal collectors the simulation will be run once more with a 100kWe CHP and then CCHP system.

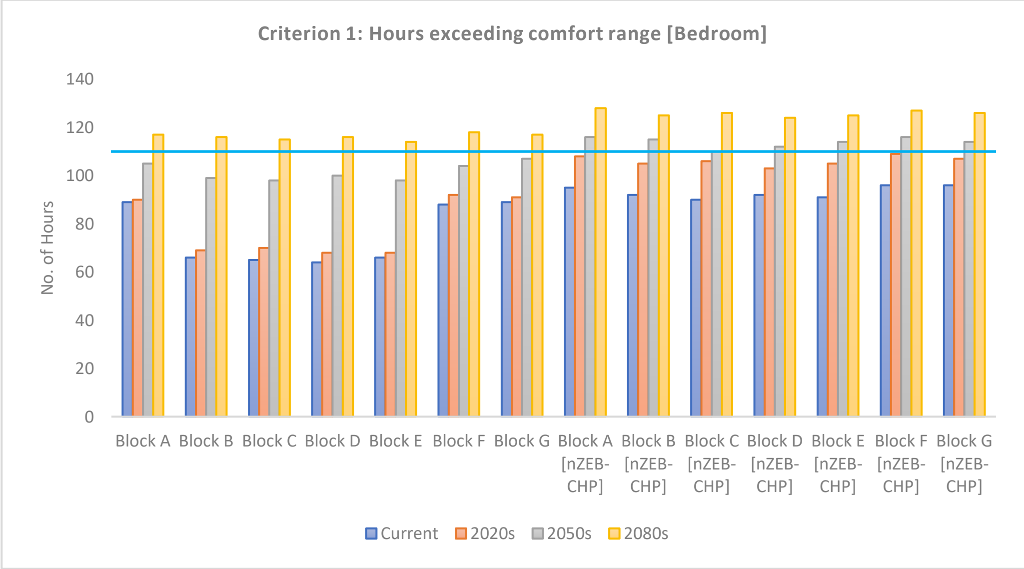
As seen from the above results, within the nZEB building, there is a high summertime demand for cooling and year-round daytime electricity for artificial lighting and equipment throughout the premises. Heating output can therefore be used for cooling using an absorption chiller during the non-heating season. Meanwhile, because the heating demand remains high during the colder months this can still be provided by the CCHP unit. By utilising the excess heat for cooling this eliminates the risk of heat being wasted or dumped. Studies have concluded that selection of a C/CHP system will depend on several factors, in particular, the heating and cooling demand of the building. A CHP system will be more appropriate and should be incorporated in a building with considerable heating demand and moderate/no cooling demand. On the other hand, a CCHP system will be more appropriate in applications with equally considerable heating and cooling demands.

Comparing the performance of the building with CHP and CCHP against the TM59 overheating criteria it becomes apparent that the CCHP system outperforms the CHP significantly as shown by Figure 4.16 and 4.17. As expected, with the CHP system in place, the building continues to overheat in the same way it did whilst the PV system was utilised instead. However, as mentioned the main difference is the fact that the PEC did not increase, thereby making it a better alternative [as shown in Figure 4.18]. The CCHP system on the other hand can ensure that the building does not fail the overheating criteria under the current, 2020s, 2050s, and 2080s weather databases. Out of the mitigating strategies that have been examined throughout this investigation the incorporation of the CCHP system is the only alternative that meant the building passes the criteria. Moreover, the baseline building bedroom [criterion 2] and kitchen [criterion 1] failed to pass the TM59 overheating criteria, meaning that the CCHP alternative is once again the only mitigating strategy that fully passed the overheating criteria whilst ensuring the PEC of the building meets the nZEB standard under current and future climatic conditions.

Looking at Figure 4.18 both the CHP and CCHP have reduced the PEC of the building under current weather conditions but more importantly they both maintained the PEC so that it meets the required nZEB standard under future climatic projections. This alone is an improvement from the previous set of results whereby the nZEB target is exceeded under future projections. Despite this significant improvement, it seems that the CCHP system is more compatible with the heating/cooling demands of this building. The PEC increased by less than 3% with CCHP, meanwhile, it increased by more than 5% with the CHP system.

It must be noted that there are problems associated with the use of a CCHP during summer within cities such as London. This is primarily due to the extra firing of boilers and pumping heat into the air to cool the building which exacerbates that urban heat island effect. Nonetheless, if the use of CCHP systems is to become widespread, alternatives to the absorption chiller-based system are available to overcome the heat island effect and attain an even higher seasonal efficiency of the system. The most successful and currently used alternative approach involves the utilisation of aquifer thermal energy storage (ATES). In an ATES based system excess heat is pumped into aquifers during the non-heating season and extracted once again for heating during the winter. This approach has been successfully applied in the Netherlands and within a social housing scheme in West London [Clark, 2007].

In terms of applicability to other buildings, CCHP may not be suitable for other residential and commercial buildings such as schools, semi-/detached dwellings, and offices and within dominantly cold or hot climates. The reason for this is because the heating, cooling, and electricity demand must be consistent all year-round to ensure the system is being used to its full efficiency. Furthermore, with a fossil fuel being used as an input source, CCHP cannot be considered an ultimately sustainable solution. Recently, other options such as a solar co-/trigeneration system has been introduced [Siegel, 2019]. Certain biomass options can also be utilised instead to ensure the system is energy sustainable. If the use of CCHP as a solution becomes widespread, these alternatives should be considered to aid in the transition towards an energy sustainable future. For these reasons it is understandable that the current available nZEB definitions do not stipulate the use of CCHP as an ultimate solution to reaching the standard.



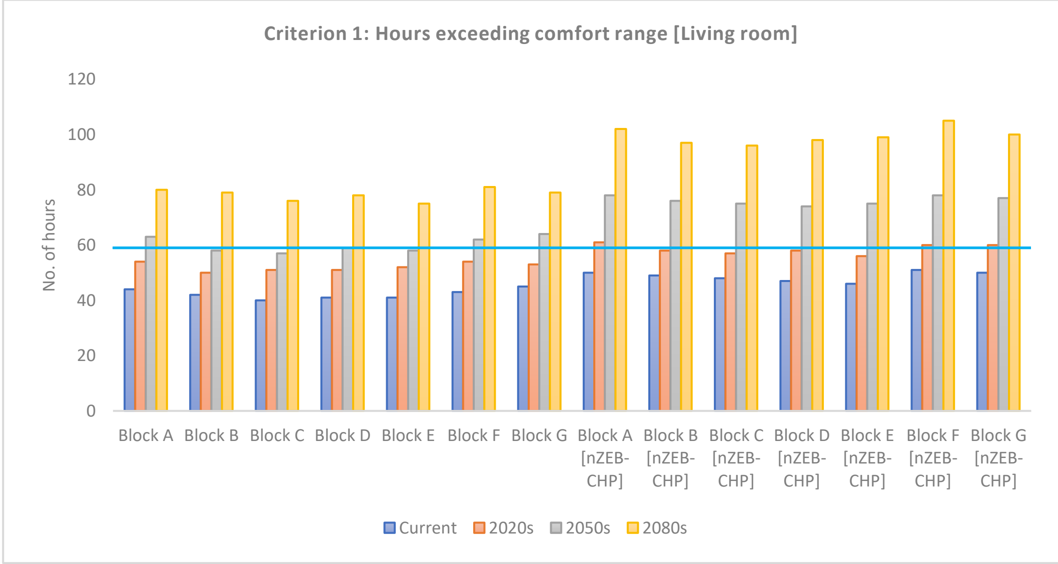
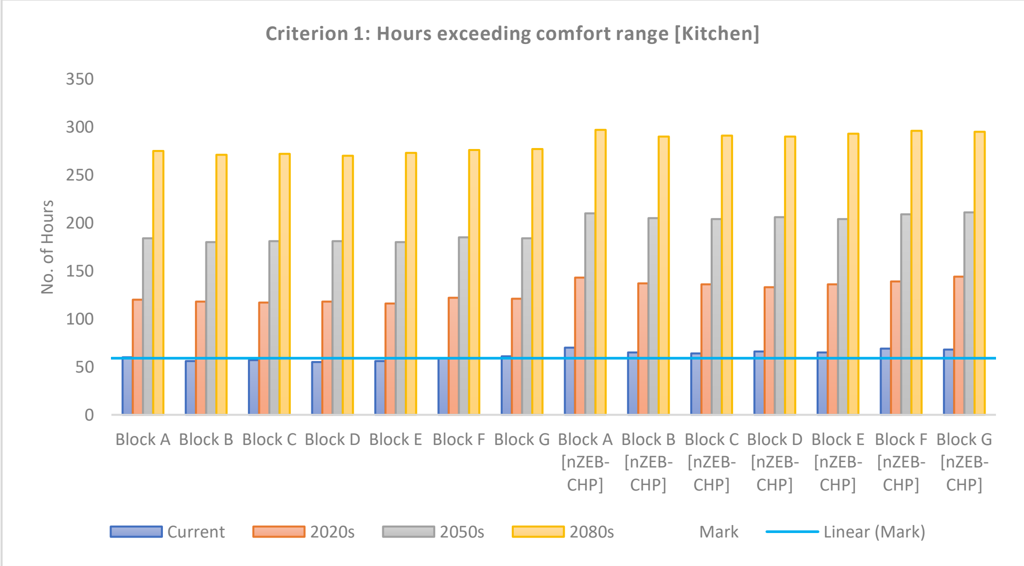


Figure 4.16a: Cibse TM59 overheating criterion 1 results for bedroom (average)

Figure 4.16b: Cibse TM59 overheating criterion 1 results for living room (average)



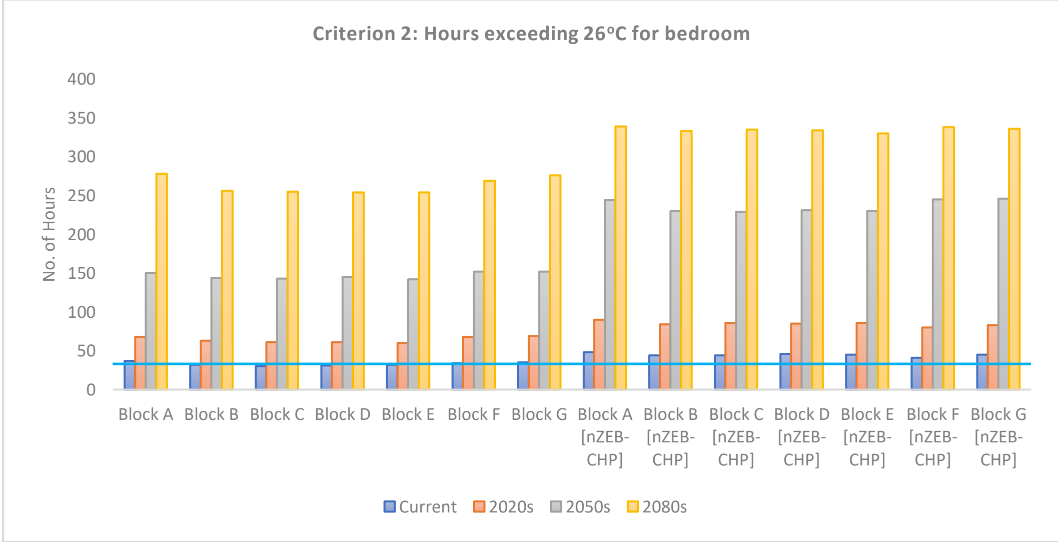


Figure 4.16c: Cibse TM59 overheating criterion 1 results for kitchen (average) conditions

Figure 4.16d: Cibse TM59 overheating criterion 2 results for bedroom (average)

Figure 4. 16: Cibse TM59 overheating criterion 1 and 2 results within the village as built and after nZEB retrofit with CHP under current and future climatic conditions

Figure 4.17a: Cibse TM59 overheating criterion 1 results for bedroom (average)

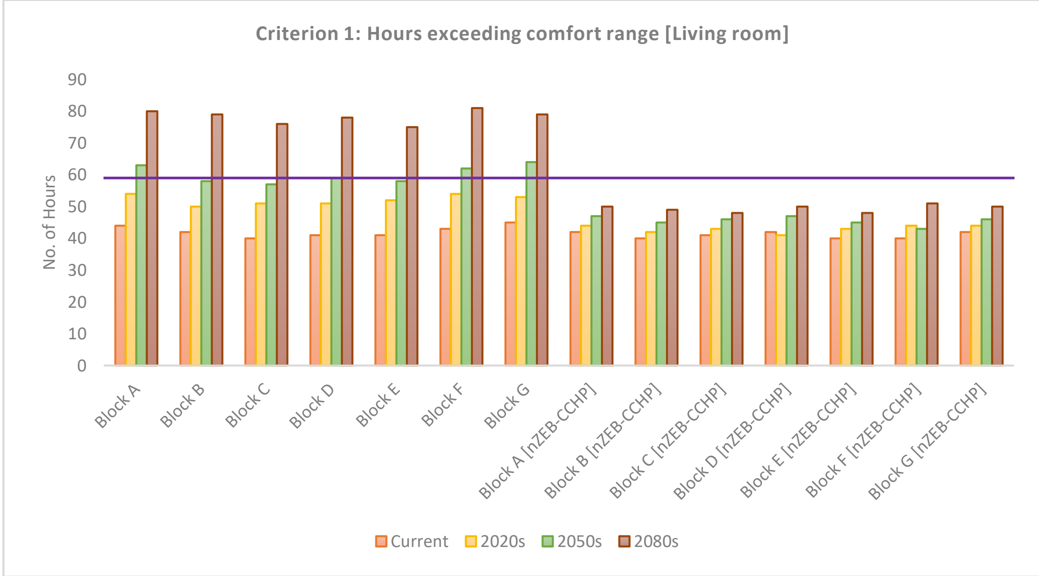


Figure 4.17b: Cibse TM59 overheating criterion 1 results for living room (average)

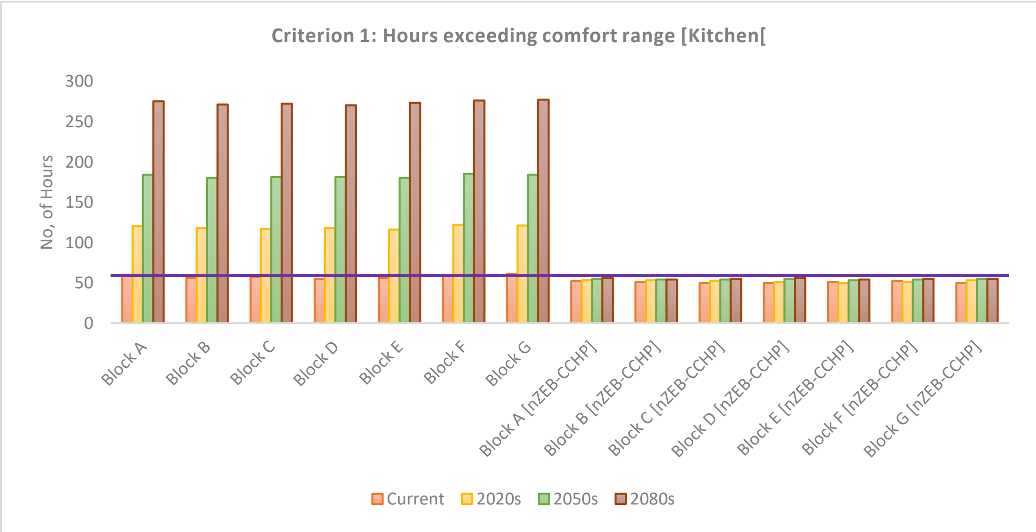


Figure 4.17c: Cibse TM59 overheating criterion 1 results for kitchen (average)

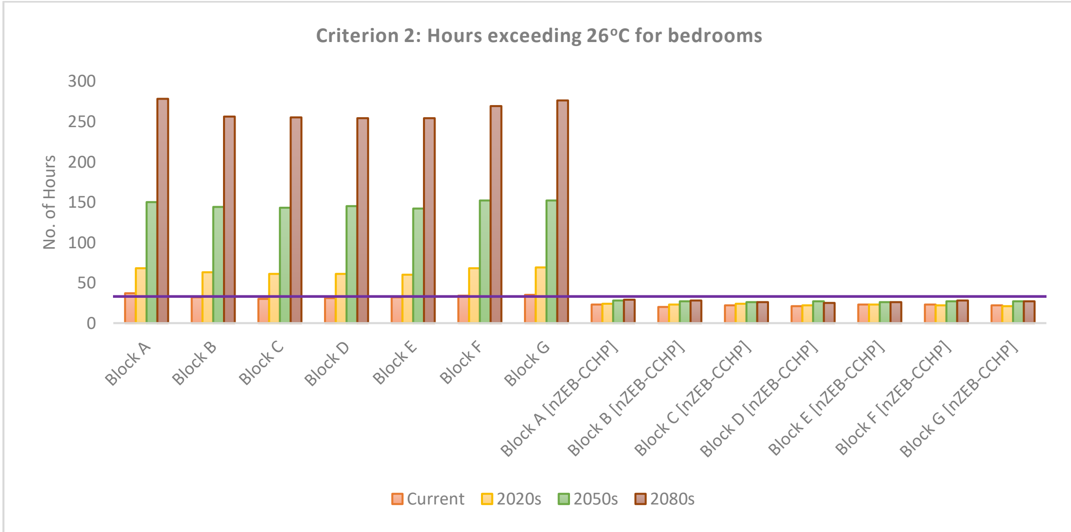


Figure 4.17d: Cibse TM59 overheating criterion 1 results for bedroom (average)

Figure 4. 17: Cibse TM59 overheating criterion 1 and 2 results within the village as built and after nZEB retrofit with CCHP under current and future climatic conditions

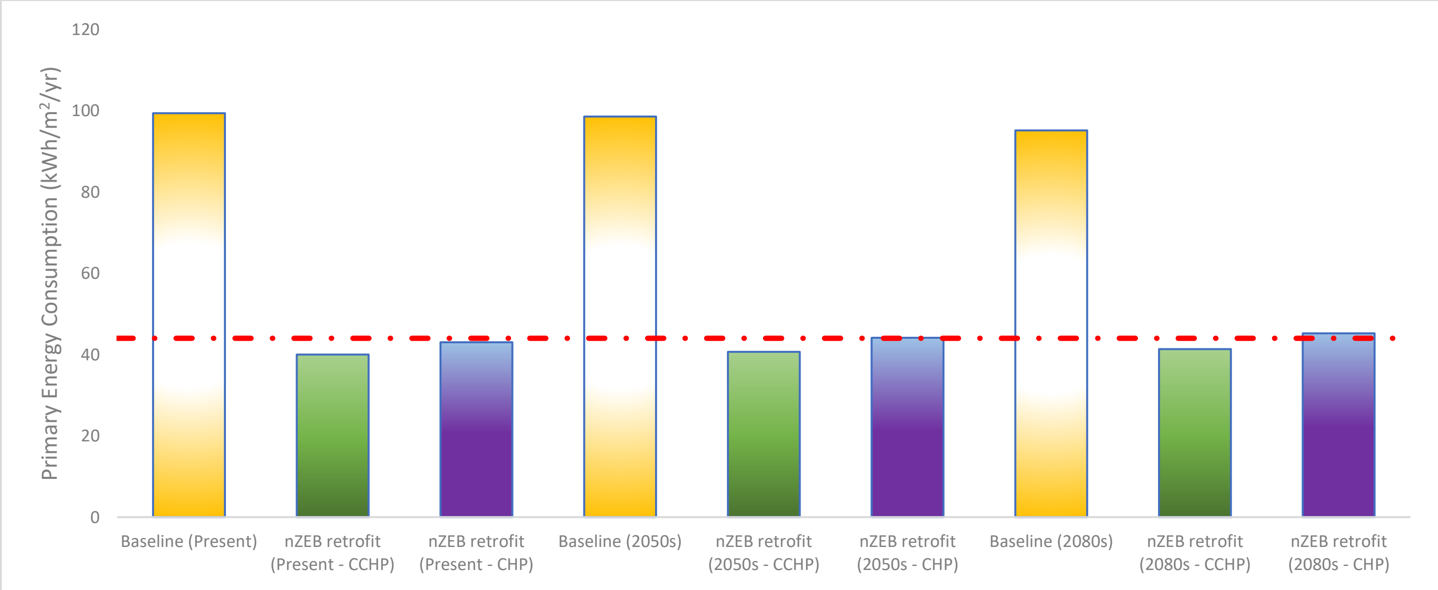


Figure 4. 18: Comparison of the primary energy consumption of the retirement village as built and after nZEB retrofit with CHP and CCHP under current and future climate conditions

4.9. Summary and Conclusion

This section investigated the impacts of a changing climate on the risk of overheating and energy performance for a UK retirement village. Using computational fluid dynamic software Tas, Edsl the energy performance of the village as it currently stands and as a nZEB was examined and compared. Reviewing the current state of the art demonstrated that once retrofitted to the nZEB standard the building would most likely experience severe overheating. The typically recommended mitigating strategies were therefore incorporated as part of the retrofit measures. The overheating criteria utilised is the “CIBSE TM59 Design methodology for the assessment of overheating risk in homes.” Once the initial set of results were obtained it showed that the use of overnight natural ventilation, double glazing, and shading devices were not sufficient to reduce the occurrence and severity of overheating throughout the village.

Overheating occurred for both the base case and the nZEB retrofit scenario. Severe overheating is experienced under the 2050s and 2080s weather projections for the nZEB scenario in comparison to the base case. For the bedroom and the kitchen overheating is experienced under the current, 2020s-2080s weather files for the nZEB scenario. Meaning that after the nZEB retrofit the building completely failed to pass the criteria. It is noted that building material seemed to influence the risk of overheating. The kitchen and bedrooms were more prone to experience severe overheating.

A 100kWe CHP and then CCHP system were simulated as part of the nZEB retrofit package. Both the CHP and CCHP have proven to work successfully in reducing and maintaining the PEC of the building under future weather files. However, the CCHP is the only mitigating strategy that fully passed the overheating criteria whilst ensuring the PEC of the building meets the nZEB standard under current and future climatic conditions, thereby surpassing the baseline building as well.

Whilst the cooling demand of the building increased substantially under future weather projections the heating demand did not significantly decrease in the same way. This means that carrying out energy efficient retrofits that consider lowering the energy demand of the building first and foremost by improving insulation and glazing etc. is still an important and relevant strategy to ensuring that energy targets are met. This is very apparent by the fact that the baseline building still experienced overheating. If mechanical ventilation or air-conditioning were a part of the baseline model that PEC would have experienced a substantial increase (far more than the nZEB alternative). In real life the majority of buildings do end up incorporating air-conditioning under hotter weather conditions as discussed in the literature review, meaning that the performance of the baseline building would have been significantly worse than the nZEB model.

The results of this section therefore do not undermine the importance of continuing to improve the energy efficiency of existing buildings but rather highlight that the approach undertaken should be reconsidered. Moreover, this does not mean neglecting lowering the energy demand but searching for and selecting mitigating strategies that will work to reduce the risk of overheating.

This investigation did not consider user behaviour and interaction as a possible mitigating strategy due to the vulnerable population demographic. Further research that collects and examines user behaviour on overheating should be undertaken to assess the significance of occupant behaviour on overheating within buildings. This should then be used in conjunction with data obtained from simulation models to determine a combined approach to mitigating the risk of overheating within buildings. Approaches that include user behaviour will lead to a decrease in costs, and although not applicable to this particular case study, they can be applied within many residential dwellings.

4.10 Chapter Summary

This chapter studied 7 residential houses and a retirement village case study. The case studies were all modelled and investigated to explore the various research questions set out the beginning. It presented the results and analyses and the conclusions for each investigation carried out. Overall, the presented case studies demonstrated that the nZEB standard is achievable with cost benefits. The methodology utilised can be replicated with other residential buildings. The creation and use of a homogeneous cost database for such UK retrofit projects would increase the reliability of cost calculations. The cost implications could then be made applicable to many buildings of similar stock. There are numerous negative consequences associated with increasing overheating. It is clear that whilst carrying out energy-efficient retrofitting of properties may be necessary to aid in the transition towards an energy-sustainable future, design choices and recommendations may need to be reconsidered so that buildings can continue to perform under variable weather conditions. Thus, integrating mitigation strategies into energy-efficient retrofit is necessary. Most importantly, retrofitting which focuses only on adapting to hotter weather conditions is not a viable solution; it could lead to a substantial increase in heating demand during the heating season. Energy-efficient retrofit projects should therefore, ideally, find a balance between meeting the heating and cooling demands of the building in an energy-efficient way under current and future weather conditions.

CHAPTER 5: COMMERCIAL CASE STUDIES

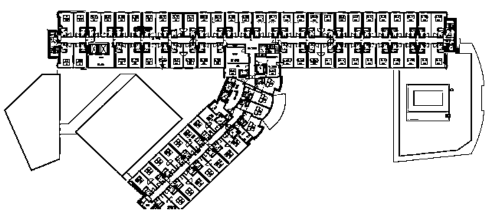
5. Chapter Introduction

This chapter introduces the commercial case studies investigated. It presents the main results obtained from the building modelling and the LCCA, where relevant. Selective tables and figures are utilised to support the discussion and analysis to answer the research questions.

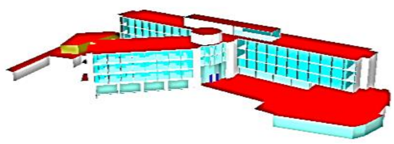
5.1. Case Study 1

5.1.1. Building Description

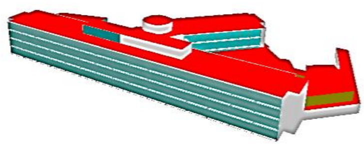
The first selected commercial building case study is Hilton Reading hotel located in Reading, Berkshire and constructed in 2009. It is a four-storey hotel, with a total floor area of 12,365m^2, and a curtain wall glazed façade system. The windows are double glazed - 4 mm clear pane; 50 mm air gap and 4 mm clear pane. Figure 5.1a shows the typical floor plan of the hotel for the first, second, and third floors which are made up of en-suite bedrooms. The ground floor is comprised of the reception area, offices, meeting, and conference rooms, changing rooms, kitchen/restaurant/bar, and fitness/sauna/pool area. The building complies with the 2006 UK building regulations; it is sealed and fully air conditioned. Air Handling Units (AHU) and Fan Coil Units (FCU), located on the rooftop, provide heating/cooling to all building floors and individual bedrooms/ meeting rooms, respectively. To meet the Domestic Hot Water (DHW) demand across the hotel, six gas fired boilers are in use.



(5.1a)



(5.1b)



(5.1c)

Figure 5. 1: (a) Typical floor plan and Tas 3D Modelling results of the hotel building (b) front elevation and (c) rear elevation

With an occupancy rate of 90% and constant electric and heat demand and seasonal cooling loads, the case study building, Hilton Reading hotel, is a suitable candidate for the comparison of CHP and CCHP systems. As discussed earlier, C/CHP systems have great potential to optimise energy production, however they have not been commonly trialled within nZEB studies. The purpose of investigating this is, therefore, to determine the potential energy and economic benefits and penalties associated with the use of C/CHP within buildings and how these systems can be possibly utilised to bridge the gap between the technical and economic feasibility of nZEBs. As a result, although a nZEB retrofit will not be carried out for this particular case study, it still forms an essential contribution towards the recommendations and final outcomes of this project.

Part of the analysis involves the examination of the units under various climatic scenarios. These are based on future projections. For each scenario, there are three emission cases: 'Low', 'Medium', and 'High.' The projected emissions scenarios range from low-energy usage and carbon emissions to high energy usage and carbon emissions. According to the Climate Change Committee the 'Medium emissions' scenario represents a 'business as usual' increase in consumption of fossil fuels and carbon emissions and will be selected for all time periods. The lifespan of C/CHP units are typically more than 15 years [MBS, 2016], therefore the weather files to be simulated are the 'TRY London' adapted to UKCP09 'Medium' scenarios for 2020s and 2050s projections.

The co/tri-generation circuit is designed in Tas by inputting relevant component details such as 'fuel source,' 'heat: power ratio,' 'heating/cooling source capacity,' 'distribution efficiency' etc. Absorption chillers have been selected to deliver the tri-generation. With water operating as the refrigerant and lithium bromide salt operating as the absorbant. The lowest temperature range to be achieved throughout the hotel should be in the range of 6-12°C. A Coefficient of Performance (CoP) of 0.80 is used for the absorption chiller and an efficiency of 0.85 is used for the air handling unit [Cibse, 2012]. The total efficiency of the heating component is therefore estimated to be 80%

(the efficiency of the AHU) and the total efficiency of the cooling components is calculated as (0.80 x 0.85) x100= 68%.

5.1.2. Model validation

To evaluate the impact of the systems to be incorporated on the case-study building, the initial simulation is conducted to reflect the actual current state of the hotel without any alterations. To validate the simulation results obtained from Tas the simulated energy consumption value is compared with the actual building's energy consumption. The simulation model is thoroughly populated to reproduce all the characteristics and systems of the building as built. The total energy consumption value considers heating, cooling, auxiliary, lighting, DHW, equipment, and is the net of any electrical energy displaced by the C/CHP generators (if applicable). The carbon emissions are calculated based on considerations such as the type of building systems, air/ plant side HVAC control(s), building envelope elements (insulation, glazing etc.), lighting/daylighting interaction(s), energy consumption, occupancy schedule, and fuel type. (Edsl, Tas, 2018). Despite this, from Figure 5.2, it can be seen that the energy consumption of the baseline model obtained from Tas is lower than the building's actual consumption by almost 30% which is mainly due to the omission of energy uses such as catering services. Catering services are one of the main energy consuming activities in hotels after heating, including hot water, cooling, and, lighting [HES, 2011]. This is corroborated by Rotimi et al. [2017] who demonstrated that the performance gap between actual data and simulation model can be significantly improved by considering catering energy use.

Thus, to improve the result obtained for the baseline model and decrease the discrepancy between simulation and actual consumption, the catering energy use is considered by adopting a benchmark value from CIBSE TM50: Energy Efficiency in commercial kitchens [Cibse, 2009b]. The operational energy usage benchmark per meal served for a 'good practice, business/holiday hotel' facility is 1.46kWh for electricity and 2.54kWh for fuel. This benchmark along with the actual average number of meals served in the hotel have contributed to a significant improvement in the estimated energy consumption value with the percentage error being reduced to 10%.

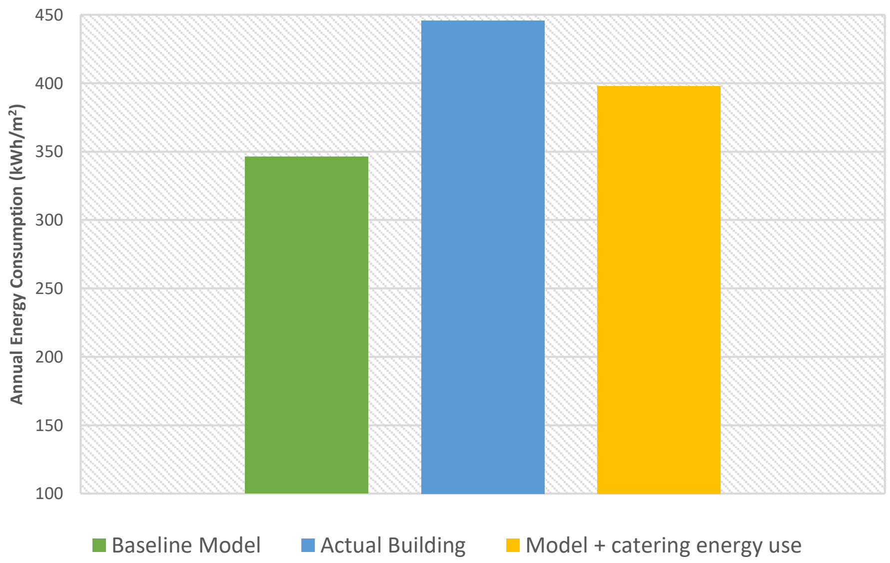


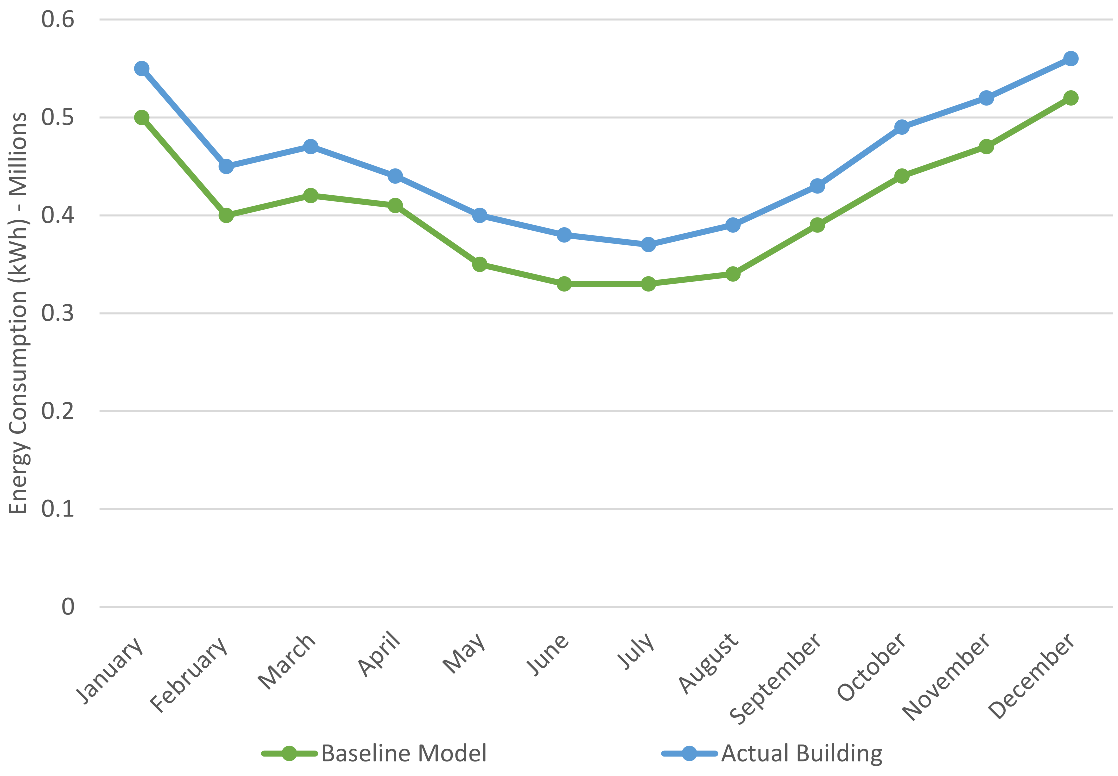
Figure 5. 2: Annual energy consumption of Tas baseline model against actual building consumption

$$Percentage\ Error: \frac{353.10 - 445.91}{353.10} x100 = -26.28 \ldots \% \tag{5.1}$$

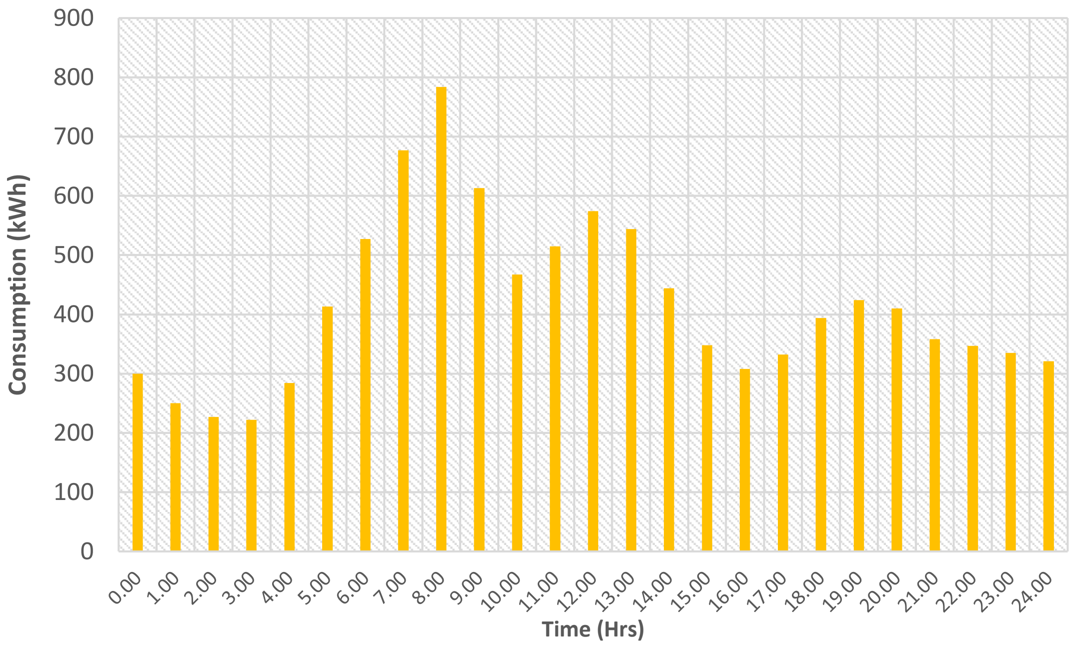
$$Percentage\ Error\ (Incl. catering\ energy\ use): \frac{404.75 - 445.91}{404.75} x100 = -10.17 \ldots \% \tag{5.2}$$

Even though this 10% is an underestimation of the actual average energy consumption of the building, it should be noted that the accuracy of the simulation results also depends on factors such as the weather data used for the simulation which should ideally replicate the microclimate of the building's location and actual occupancy rates. This is challenging to achieve and can lead to the variation between simulated and actual energy consumption.

5.1.3. Energy and Carbon Emission Contribution Of CHP vs CCHP



(a)



(b)

Figure 5. 3: (a) Model monthly energy consumption and actual building energy consumption and (b) Model July hourly heat consumption

After validating the baseline model, the CHP and CCHP systems were initially sized to deliver a constant base heat load for the building as discussed previously. To do so, the breakdown of the monthly energy consumption is explored to identify the month when the base heat load consumption is likely to occur. Looking at Figure 5.3a it can be seen that for both the Tas system model and actual building consumption, July overall has the lowest consumption in comparison to other months. Subsequently, the hourly heat consumption, obtained from Tas, is examined to identify the base load, and select the initial system size. It is recommended that the base heat load is selected from the estimated hours of use for the unit. Therefore, looking at Figure 5.3b the base heat load between 07:00-00:00 hours occurs at 16:00 hours and is 246kWh. Based on this, the initial system will be sized as a 150kWe unit which is selected by examining typical C/CHP unit ratings and matching their thermal output to the base heat load of the building [CIBSE GPG 388, 2012; DUKES, 2017]. Although the monthly heating consumption could have been examined to identify the base heat load, it is recommended for maximum accuracy that the hourly (and if possible half-hourly) consumption is utilised instead [CIBSE GPG 388, 2012; Hopkins, 2016]. Once the initial size is established, smaller and larger sized systems are trialled to assess the impact this would have on the performance of the building in terms of energy consumption, carbon emissions and for the financial analysis.

Figure 5. 4: (a) Comparison of the performance of various sized CHP and (b) CCHP systems in terms of energy consumption and emissions and (c) primary energy consumption with CHP versus CCHP

From Figure 5.4 the general trend observed is that as the size of the CHP and CCHP systems increase, the energy consumption of the building increases. The comparison of Figure 5.4a and 5.4b illustrates that incorporating a CCHP system leads to a lower energy consumption value for a similar sized CHP system when the energy consumption of the existing chiller is considered. If the baseline building did not have an existing chiller, the energy consumption with CCHP would have been higher. This suggests that the CCHP system is an advantageous solution when incorporated in a building with existing constant or seasonal cooling demand. On average the CHP system contributed to a 10.4% increase in energy consumption.

Looking at the carbon emission reductions it is clear that both systems contribute to considerable reductions. The average percentage decrease of carbon emissions with CHP is 32% and with CCHP it is 36%. The larger sized systems contributed to a larger percentage of carbon emission reductions, despite the increase in fuel input, because of two main reason. Firstly, the thermal energy produced by the systems displaces combustion of the fuel that would otherwise be consumed in an onsite boiler; therefore, a larger sized system increases the boiler fuel emissions savings [EPA, 2015]. Secondly, the carbon emissions production with C/CHP units considers the grid displaced electricity emission savings, therefore, as the size of the unit increases the savings also increase [Carbon Trust, 2016]. Despite this, the average difference, in terms of emission reductions, between the smallest unit and the largest unit is less than 13%. Meaning that the larger systems' contribution towards reducing emissions is not significant enough to justify their incorporation. This, in addition to the excess heat generation that occurred with the larger units illustrates the importance of selecting an appropriately sized unit that matches the building's energy requirements as opposed to over-sizing or under-sizing the selected system.

As discussed earlier based on the requirements of the EPBD the energy performance of a building should include a numeric indicator of primary energy use and within the literature it is agreed upon that the main indicator to be used to assess whether the building has reached the nZEB standard will be the PEC. The average percentage decrease of PEC with CHP is 40% and with

CCHP it is 52%. Figure 5.4, therefore, reflects the true potential these systems have in being able to reduce the primary energy consumption (PEC).

5.1.4. Performance Under Future Climatic Conditions

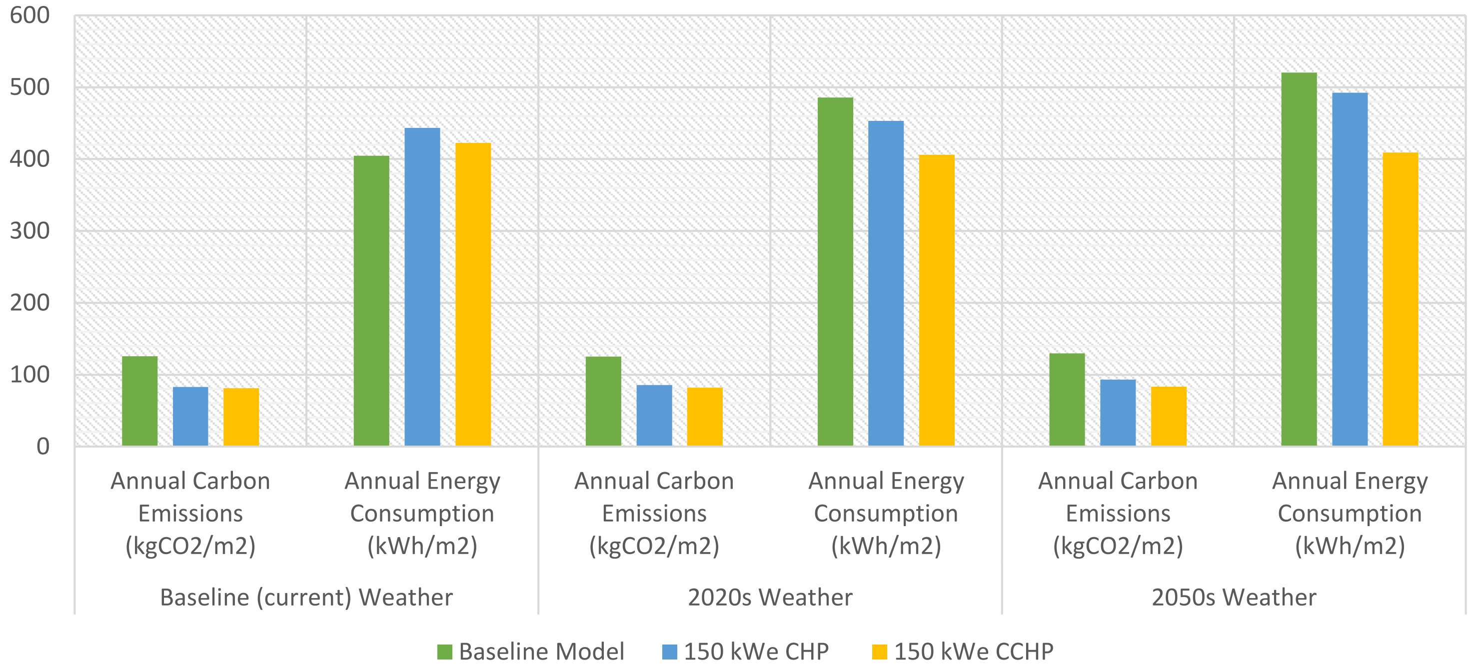


Figure 5. 5: Comparison of building performance for baseline and future climatic scenarios without C/CHP against with CHP and CCHP

Figure 5.5 presents the results of the performance of the building with and without the 150kWe CHP and CCHP systems under future climatic projections. The purpose of simulating the building once again with the two systems is to consider the impact of a changing climate on key building performance parameters. The projections showed a constant increase in temperature over stipulated timelines. Whilst this caused the annual heating demand and carbon emissions due to heating to marginally decline, the cooling demand increased substantially.

It is interesting to observe that between the CHP system and the CCHP, the latter's performance in terms of energy consumption and carbon emissions, remained unaffected under future climatic timelines. In fact, the CCHP unit's useful power output increased by approximately 12% under future climatic projections (particularly during the summer months) with very little/no increase in fuel consumption. Looking at Figure 5.5 there is an increasing trend of energy consumption and carbon emissions as future timelines are simulated regardless of whether a co/tri-generation system is in place. The key findings from this were that the average percentage increase for the annual energy consumption with CHP is 13.48 and 16.65 percent for the 2020s and 2050s weather projections, respectively. Meanwhile, the average percentage increase for the annual energy consumption with CCHP is almost negligible; with the largest difference between the baseline weather file and the 2080s weather projection being 1.10%. A similar increasing trend in the case of the building emission rate is observed with CHP of 4.28 and 12.04 percent for the 2020s and 2050s weather projections, respectively. Contrariwise, the average percentage increase for the annual carbon emissions with CCHP is 0.95 and 1.62 percent for the 2020s and 2050s weather projections, respectively.

It should however be noted that the results generated do not consider the projected decarbonisation of the grid. According to International Tourism Partnership's (ITP) Hotel Decarbonisation Report [2017] if the 'Sectoral Decarbonisation Approach' scenario to meet the limiting of global temperature rise to 2^{o}C is accomplished, then it is expected that there will be a 40% decarbonisation of the grid by 2050. Moreover, the Department of Business Energy and Industrial Service's (BEIS) Energy and Emissions Projection (EEP) report [2018] has projected that the Grid Carbon Factor will decrease from 212 grams to 66 grams between 2017 and 2035. Furthermore, DEFRA [2016] reported that in 2016 it was already cheaper to run electric heating than gas heating (if using a ground source heat pump) and it is expected that by 2020 using grid electricity will lead to lower emissions in comparison to burning natural gas on site. This may indicate that eventually C/CHP units will no longer make an effective contribution to reducing emissions. Nonetheless, this should not undermine the potential energy and cost benefits of incorporating C/CHP systems because it has been recognised that those systems can be seen as vital "transitional measures" that can offer significant contributions in the long-term towards a sustainable and low emissions energy system [Hawkes, 2010; Harrison, 2011; Staffell, 2017].

Furthermore, it is worth noting that the baseline model (without C/CHP) had a percentage increase of 30% in energy consumption from the baseline weather scenario to the 2050s weather projection. Even though the 'Medium' emissions timeline scenario is selected and not the 'High.' Selection of the 'High' timeline scenario would have contributed to an even more significant increase in energy consumption and carbon emissions. This is because of the considerable increase in projected temperatures from the 'Medium' to the 'High' timeline scenario. Nonetheless, this demonstrates that the incorporation of either the CHP or CCHP system is advantageous to maintaining the overall performance of the building even under potentially different climatic conditions.

5.1.5. Simple Financial Analysis

Whilst the capital investment costs of C/CHP systems are considerably higher in comparison to conventional boilers, these systems have been proven to yield significant cost savings [Gu et al. 2014; Maraver et al. 2013]. However, this is highly dependent on whether the system is implemented in an application where the heat is efficiently utilised. Therefore, for all the investigated systems, it is essential that a financial appraisal is conducted to confirm which system is the most advantageous to implement. A payback methodology is adopted. This type of analysis is a useful tool in assessing the economic viability of the systems and suitability of the selected size [Jing et al. 2012; María, Jose, and Eva, 2017]. Net benefits per annum are also calculated to determine whether investing in the systems is a beneficial and practical option financially. The payback period is calculated following Equations 5.3-5.8 which have been adopted and reproduced from the CIBSE GPG 388 [2012].

$$\boldsymbol{Payback\ (years)} = \frac{\boldsymbol{Capital\ Cost}(£)}{\boldsymbol{Net\ benefit\ per\ annum}} \tag{5.3}$$

$$Net\ benefit\ per\ annum\ = \sum savings\ - \sum Costs \tag{5.4}$$

$$\sum savings\ = Displaced\ Electricity\ savings\ x\ Displaced\ Boiler\ Fuel\ Savings \tag{5.5}$$

$$= [Electricity\ Output\ [kW_e\ x\ hrs\ run] x\ Elcetricity\ cost] \tag{5.6}$$

$$x\ Displaced\ Boiler\ Fuel\ \left[\frac{kW_t\ x\ hrs\ run}{efficiency\ of\ existing\ boiler}\right] x\ Gas\ Cost$$

$$\sum Costs\ = C/CHP fuel\ cost\ x\ Maintenance\ Cost \tag{5.7}$$

$$= [Gas\ input\ [kW_t\ x\ hrs\ run] x\ Gas\ Cost] x\ [Electricity\ output\ x\ Maintenance\ Cost] \tag{5.8}$$

Possible grants/loans were not taken into consideration; however, the Climate Change Levy (CCL) exemption rates have been applied. CCL rates [2018] have been obtained as shown in Table 5.1 and incorporated into the final calculations because all the examined systems reach the threshold criteria for Good Quality CHP [UK GOV, 2018]. The CHP Quality Assurance programme (CHPQA) evaluates systems (<2MWe) on having a Quality Index (QI) rating of at least a 100 and power efficiency greater than 20% [Burns, 2017]. The units will operate for 17 hours per day between 07:00-00:00 because operating outside those hours would lead to financial losses.

Table 5. 1: Summary of financial assumptions

Gas Cost (pence/kWh)	3.50
Electricity Cost (pence/kWh)	10.30
Maintenance Cost (pence/kWh)	0.90
Climate Change Levy (CCL) rate for gas (pence/kWh)	0.203
CCL rate for Electricity (pence/kWh)	0.583
C/CHP installation cost (£/kWe)	500-1200
Anticipated running hours	17 hrs per day

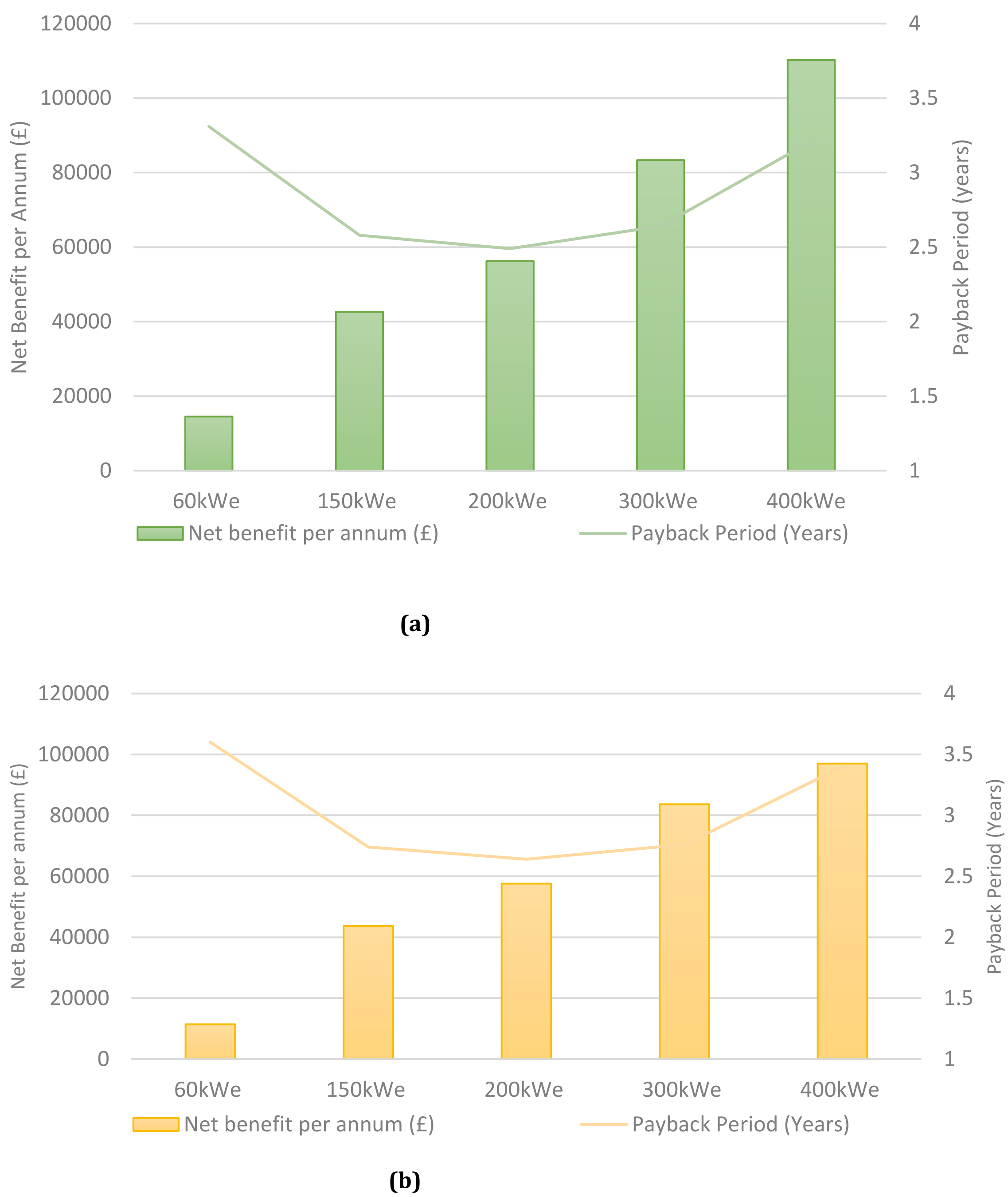


Figure 5. 6: (a) Comparison of net benefit per annum and payback calculation for CHP and (b) CCHP

Figure 5.6 presents the results for the payback period and yearly net benefits for all the evaluated C/HP systems. The relationship between the payback period and the size of the system is highlighted. That is, an 'appropriately' sized system will lead to shorter payback periods when compared to an under-sized or over-sized system.

For both the CHP and CCHP systems, the 300 and 400 kWe units had the longest payback period in comparison to all the other units, despite the considerable savings accrued. This is because when an over-sized system is incorporated the sum of the cost increases leading to longer payback periods. Moreover, whilst this did not occur for any of the examined systems, it is possible that a grossly over-sized system will not qualify for the CCL exemption as the QI and power efficiency will be lowered.

Despite the lower costs, the 60 kWe units had a longer payback period in comparison to the 150 and 200kWe units because of the significant reductions in total savings which lead to reduced net benefits and longer payback periods. In addition, the need to purchase electricity and rely on supplementary heat from the boilers further decreases the energy and financial benefits.

The 200kWe CHP and CCHP units had the shortest payback period in comparison to all the other units, suggesting that to obtain maximum financial benefits the 200kWe system would be the most efficient solution for this hotel.

Between the CHP and CCHP units, the payback period for the CCHP units is longer. Furthermore, the comparison of the net benefits between the CHP and CCHP systems from Figure 5.6a and 5.76 shows that between the two systems, the CHP system offers a 5% increase in net benefits. This is because of the added capital investment costs and operating costs associated with the absorption chiller, for the CCHP units.

Overall, the payback analysis indicates that regardless of which system is selected it is in fact cost-effective and will offer financial benefits. Furthermore, the results highlight that looking for a solution with the lowest initial capital investment cost is an inadequate indicator of actual cost effectiveness. Consequently, it is essential that the cost analysis is fully explored so that the true risks and benefits may be investigated, rather than just taking into consideration surface values such as the initial investment; because this type of analysis does not represent the true financial viability of the measures.

5.2. Summary and Conclusions

The main objective of this investigation was to compare the performance of CHP and CCHP systems on an existing UK hotel to assess which of the two systems offer the best solution depending on energy, financial, and carbon emissions savings.

The incorporation of both the CHP and CCHP systems contributed to an increase in the energy consumption and a decrease in the carbon emissions and primary energy consumption. It is also clear that a CCHP system contributed to lower energy consumption values for a similar sized CHP system, due to the decreased use of the existing chiller. On average the CHP systems reduced carbon emissions by 32% whilst the CCHP systems led to a 36% decrease.

Similar to the first residential case study investigated, simulation of the baseline model and the model with C/CHP systems under different climatic scenarios showed a progressive increase in the energy consumption and carbon emissions of the building. Once again, most of the energy consumption is a result of heating demand, which is expected due to the UK's cold dominant climate. However, because the most optimistic future projections quote an increase in temperatures, it is plausible that there will be a shift from high heating demand to high cooling demand. Therefore, whilst the CHP system is a viable solution under current climatic conditions; if average temperatures do rise, as projected, incorporation of a CHP unit may no longer be an advantageous solution. This is clear since the CCHP unit led to a higher building performance under future timelines in comparison to the CHP unit. This, in turn, indicates the CCHP system is more appropriate when incorporated in a building located in a hotter climate/ shorter wintry conditions. Meanwhile, the CHP system is more efficient with longer periods of wintry conditions. It should also be noted that the type of building being assessed and its 'form' (architectural style, detailing, and material) will contribute to variations in results.

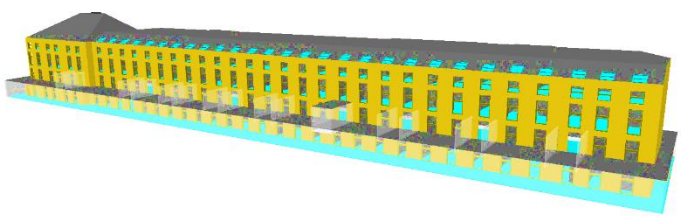
The results of the financial analysis demonstrate the importance of carefully selecting the size of a C/CHP system so that the true benefits can be attained rather than under/oversizing the systems and dealing with energy and cost losses. Based on the payback period, it is also apparent that from a financial point of view, the 200kWe system would be the best solution for this hotel.

5.3. Case study 2

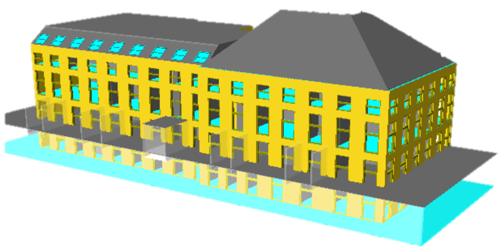
5.3.1. Building Description

The second commercial case study to be investigated is Hilton Edinburgh Grosvenor hotel located in Scotland, Edinburgh and constructed in the 1860s. As mentioned throughout the literature review, there are currently no studies investigating whether older commercial buildings can reach the nZEB standard. Hence, this study was selected to examine this and determine whether reaching the nZEB standard is indeed feasible for older commercial buildings. It is spread over two separate buildings, as shown in Figures 5.7a and 5.7b, and has a total floor area of 10,304m^2. Heating in the hotel rooms is met by a series of gas fired boilers. Overall, the hotel has 19 split AC/VRF systems serving the meeting rooms, back of house offices, server room, and front of house areas. Certain public areas of the hotel are also fitted with LED lighting. Not uncommon to older UK buildings, the type of glazing is double glazed sash windows.

Tas is used once again to predict energy performance of the building. The initially generated energy model is the reference point for improvements and is defined as the 'baseline model.' The type of weather file selected for carrying out the analysis is the Edinburgh Test Reference Year (TRY).



(5.7a)

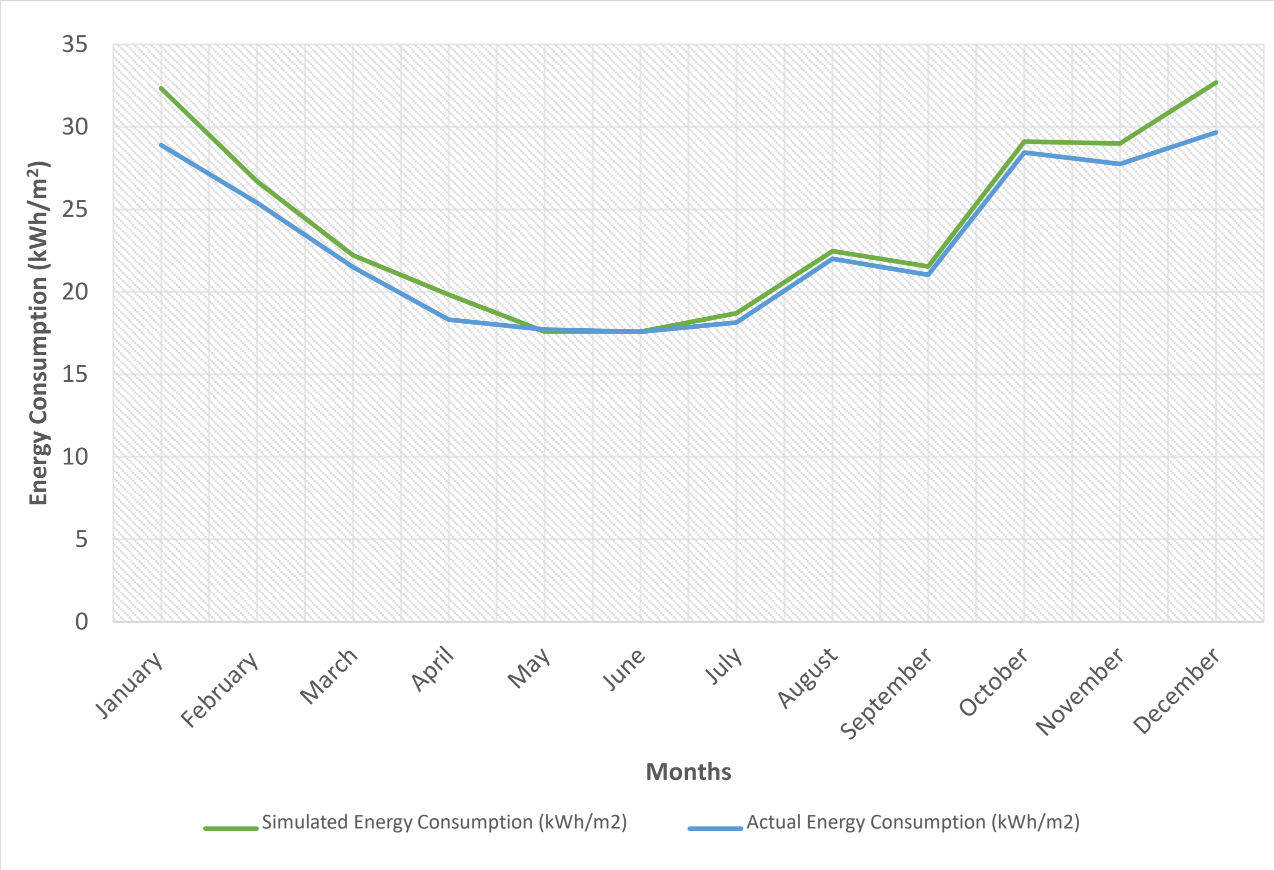


(5.7b)

Figure 5. 7: Tas 3D Model of the (a) main hotel building and (b) town-house

5.3.2. Baseline Model

To evaluate the impact of the measures to be incorporated on the case-study building, the initial simulation is conducted to reflect the actual current state of the hotel without any alterations. To validate the simulation results obtained from Tas the simulated energy consumption value is compared with the actual building's energy consumption. The simulation model is thoroughly populated to reproduce all the characteristics and systems of the building as built. Looking at Figure 5.8, the difference between actual energy consumption and simulated energy consumption is 4.60%. Even though this 4.60% is an overestimation of the actual energy consumption of the building, it should be noted that the accuracy of the simulation results depends on factors such as the weather data used for the simulation which should ideally replicate the microclimate of the building's location and actual occupancy rates [Rotimi et al. 2017]. However, this is challenging to achieve and can lead to the variation between simulated and actual energy consumption. Furthermore, the building is constructed from stone walls and there is evidence from various studies that historical stone walls have a better thermal performance than expected and obtained from standard calculations and therefore computational modelling [Li et al. 2014; Lucchi, 2017; Mantesi et al. 2018]. This is because whilst simulation models/ standard calculations consider stone walls as monolithic, in reality, the proportion of stone, mortar, and air gaps varies which in turn has an effect on the overall simulated building energy consumption.



$$\boldsymbol{Percentage\ Error}: \frac{\mathbf{289.79 - 276.45}}{\mathbf{289.79}} \boldsymbol{x100} = \mathbf{4.60} \ldots \%$$

Figure 5. 8: Simulated monthly energy consumption against actual building energy consumption and their percentage difference

5.3.3. EEMs Simulations

Figure 5.9a shows the energy consumption reduction contribution of each measure individually implemented on the case-study building in comparison to the 'baseline' energy consumption and how close this reduction is to the nZEB target. Looking at Figure 5.9a it can be observed that certain groups of measures offer a significant contribution to the reduction of energy consumption in comparison to other groups and for certain groups of measures, such as the microgeneration systems, the energy consumption increases.

However, this is not a true reflection of the contribution these systems have to offer. Figure 5.9b illustrates the significant reduction in PEC reduction that is achieved with the CHP and CCHP systems. Although only one measure is simulated on the building, the PEC is reduced by an average of 50% and 55% with CHP and CCHP, respectively, meaning that it almost reaches the nZEB target of 60% reduction in PEC. Similarly, all the differently sized CHP and CCHP units offered the largest contribution to the reduction of CO_2 emissions.

Figure 5.9d represents the energy savings against the cost savings of the EEMs and shows that generally the energy and cost savings are the lowest for insulation, lighting, and glazing. For each of the EEMs the savings in energy are calculated by evaluating the difference in energy consumption with the EEMs and the baseline energy consumption. The annual electricity and gas price savings are obtained by multiplying the consumption savings with the corresponding fuel price which is 10.30 pence/kWh for electricity and 3.50 pence/kWh for gas. The total of these savings is expressed relative to the baseline model as presented in Figure 5.9d.

For most measures, the energy and cost savings are positively correlated. Thus, measures with higher energy savings also have high cost savings and vice versa. However, this is not the case for all the measures; for instance, certain measures had significant energy savings, however their cost-savings were minor in comparison. Examples of this included the biomass boiler and solar water heating (SWH). On the other hand, some measures had very little energy savings and higher cost-savings, as in the case of mechanical ventilation.

Numerous studies have demonstrated that generally EEMs should be selected based on a balance of the energy and cost-savings [Gonçalves et al. 2010; Congedo et al. 2016; Ascione et al. .2017; Salem et al. 2018a]. The comparison illustrated by Figure 5.9d therefore provides an overview regarding which EEMs should be selected to create the retrofit scenarios and which ones should be avoided. It is also highlighted that it is possible to achieve similar energy savings for lower investment costs and higher cost-savings. For example, the energy consumption reduction and energy savings with lighting in comparison to glazing is ±5% (i.e. very similar), however, the difference between their capital cost is a substantial 80% and most importantly lighting had higher cost-savings.

Because of the hotel's heritage value/significance the insulation measures are simulated as internal insulation. Despite this, it is essential that the applied insulation still demonstrates effective improvements in energy performance and value for money. The two types of insulation materials initially selected complement the existing hygrothermal behaviour of the building; therefore, the risk of interstitial condensation (which can pose health problems for occupants and damage the building fabric) is avoided. Between sheep's wool and cellulose insulation, the CO_2 emissions reduction difference were negligible, although cellulose's performance is higher by an average of 5%. The energy and cost savings of cellulose insulation, however, are higher by an average of 15% in comparison to sheep wool insulation. Therefore, based on the simulation results, the 160mm cellulose should be selected to make-up the retrofit scenarios because any further increase in thickness will not have significant/additional benefits.

The existing glazing throughout the hotel is double-glazed sash windows. Although it is not provided by all suppliers and can be costly, triple glazed sash windows are still considered an energy and cost-effective investment [HL, 2017; GBS, 2018], particularly with recent bouts of harsher weather in the UK. However, they have extremely long payback periods (30+ years) and small energy and cost-savings despite being one of the costliest EEMs. Therefore, in real life application the final decision regarding the selection of double or triple glazing will depend on several factors because whilst the U-value target may not be reached, the energy consumption, CO_2 emissions, and PEC will not be largely affected. Furthermore, the energy performance of the hotel with insulation implemented outperformed the energy performance with glazing. For example, the average energy consumption reduction with triple glazing and insulation is 7% and 13%, respectively. This suggests that improving the insulation for this building works better to lower the energy demand in comparison to improving the glazing. This is particularly true due to the existing double-glazed windows. If double-glazing is not in-use already then improving the glazing to triple glazing would have contributed to a greater reduction in energy consumption.

Furthermore, studies have shown that nZEB u-value targets are not always technically attainable or cost-effective at all particularly where double glazing is already in place [Berggren et al. 2013]. However, because the nZEB U-value target for windows is achievable if triple glazing is incorporated, for the purpose of this investigation the incorporation of triple glazed windows will not be omitted from the retrofit scenarios. Finally, although krypton filled triple glazing performed better in comparison to argon filled triple glazing, the difference, as seen by figures 5.10a, b, and d is not significant enough to justify the higher capital cost associated with krypton filled triple glazing.

Incorporating insulation and triple glazing means the airtightness of the building will become very low and that mechanical ventilation is necessary to avoid poor air quality. Based on the results it is clear that mechanical ventilation systems have the potential to reduce space heating demand. However, the energy performance of the building with MVHRV surpasses the performance with MVERV. The energy consumption reduction is 18.82% with MVHRV and 10.34% with MVERV and the CO_2 reductions with MVHRV is 9.20% higher in comparison to MVERV. Similarly, the energy and cost-savings were on average 10% higher with MVHRV.

Currently LED lighting is being used in some public areas of the hotel. The trialled simulation with LED and CFL lighting and auto-presence detection throughout the building showed reductions in energy consumption, CO_2 emissions, and energy and cost-savings that are similar to costlier measures such as insulation and glazing, as discussed previously. However, looking at figures 5.10a, b, and d LED outperforms CFL. On average LED had energy and cost-savings that were 10% higher in comparison to CFL.

The simulations showed that improving the existing boilers to being automatic/programmable controlled thermostat boilers (ATB/PTB) has the potential to offer significant improvements in the energy performance of the hotel. Looking at the results implementing heating control systems has the potential to substantially reduce energy consumption and CO_2 emissions whilst achieving high energy and cost-savings. In addition, heating controls are inexpensive relative to the contributions they offer and are known to have short payback periods if they are correctly utilised [MBS, 2018]. The automatic thermostat gas fired boiler contributed to a 27.36% reduction in energy consumption and a 14% reduction for CO_2 emissions. The overall energy and cost-savings of the automatic thermostat-controlled gas fired boiler is higher by an average of 12% in comparison to the programmable thermostat-controlled gas fired boiler.

Although the ASHP, SWH, and the biomass boiler measures contributed to some of the largest reductions in energy consumption and carbon emissions their cost-savings were significantly lower in comparison to their energy-savings as illustrated by Figure 5.9d. Therefore, this suggests that their incorporation as nZEB retrofit measures for this building is not suitable and it will not be very energy or cost-efficient. The implementation of heat pumps for the entire hotel and generally also needs careful consideration because the extra electricity consumption associated with this measure can easily outweigh gas consumption savings. Furthermore, when the energy and cost-savings of those measures are compared with those of the microgeneration systems, it is apparent that implementing a microgeneration system is the most advantageous solution.

As discussed earlier, because majority of energy demand within the building is heating demand with moderate cooling demand during some of the hotter months, the incorporation of a CCHP unit is not a suitable solution for this hotel [Maria, Jose, and Eva 2017; Salem et al. 2018b]. Instead, a CHP is more compatible with the heating/cooling demands of this building and should therefore be used for the retrofit scenarios.

Overall, the implementation of certain measures alone can almost reduce the energy consumption, CO_2, and PEC to the required nZEB target. However, looking at the figure those are typically measures that are oversized for the building's energy requirements. Most importantly, none of those measures were able to completely reduce the energy consumption to meet the required target. Thus, initially implementing the measures separately on the building, via simulation, highlights that to reach the nZEB standard several measures must be implemented together. In addition, nZEBs are intended to be 'truly' energy efficient buildings. Meaning that rather than just meeting the near-zero balance, it is vital that the energy efficiency of the building is improved, firstly, to lower the energy demand of the building; as opposed to implementing an oversized renewable/microgeneration system to meet and offset the existing energy demand. This is in consonance with the initial generic definition outlined by the EPBD [recast].

The next phase of analysis involves systematically implementing different combinations of EEMs until the nZEB target is reached. The measures will be combined initially as sets of 2 and 3 combinations until all the possible different combinations of measures have been explored to see how many EEMs are required meet the nZEB target and which combination of EEMs perform well together. Investigating the combination of EEMs in this way will also offer valuable insight regarding whether the number or type of measures combined has a more prominent influence on improving the energy performance of the building and meeting the nZEB target. Based on the above results the selected EEMs have been altered and Table 5.2 is showing the summary of the final selected EEMs.

Table 5. 2: Summary of final selected EEMs

EEMs	**Design Measure**	**Acronym**
Insulation	160mm Cellulose	CE
Glazing	Triple Glazing, 36 mm Argon filled, Low-e	TGA
Lighting	LED + Auto presence detection	LED+A
HVAC & DHW	Automatic Thermostat controlled direct gas fired Boiler	ATB
Microgeneration	200kWe CHP	CHP

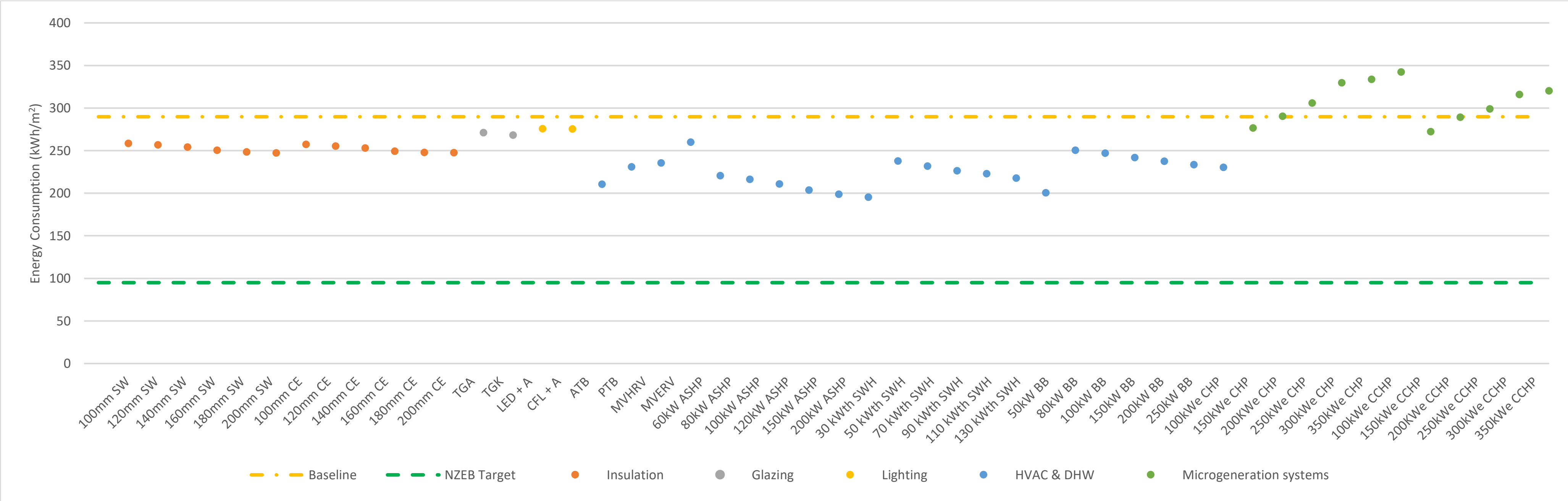
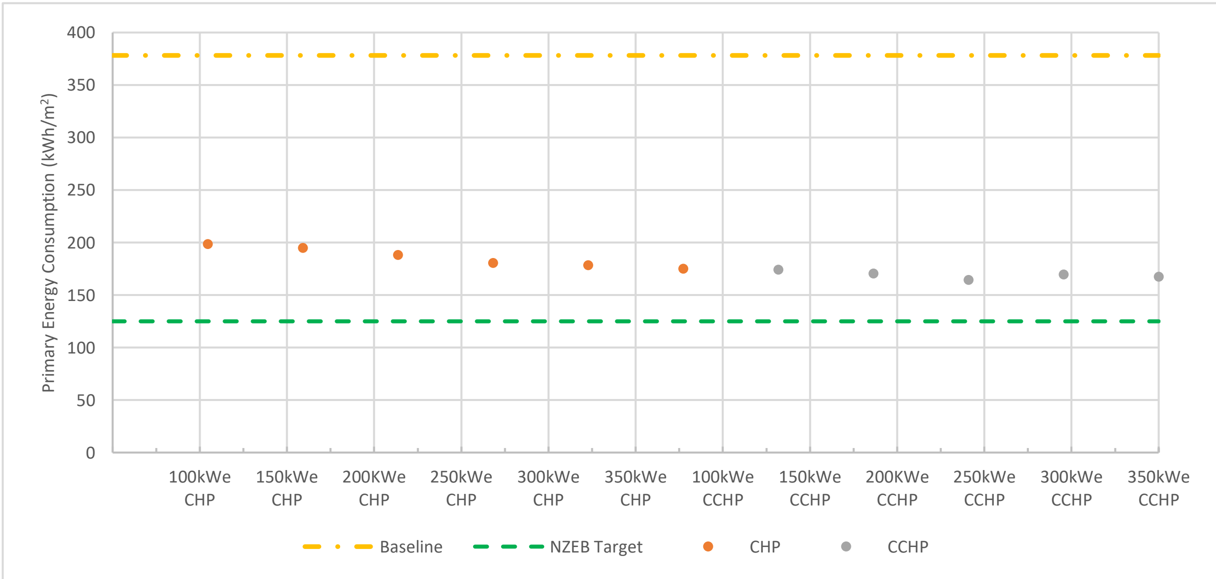
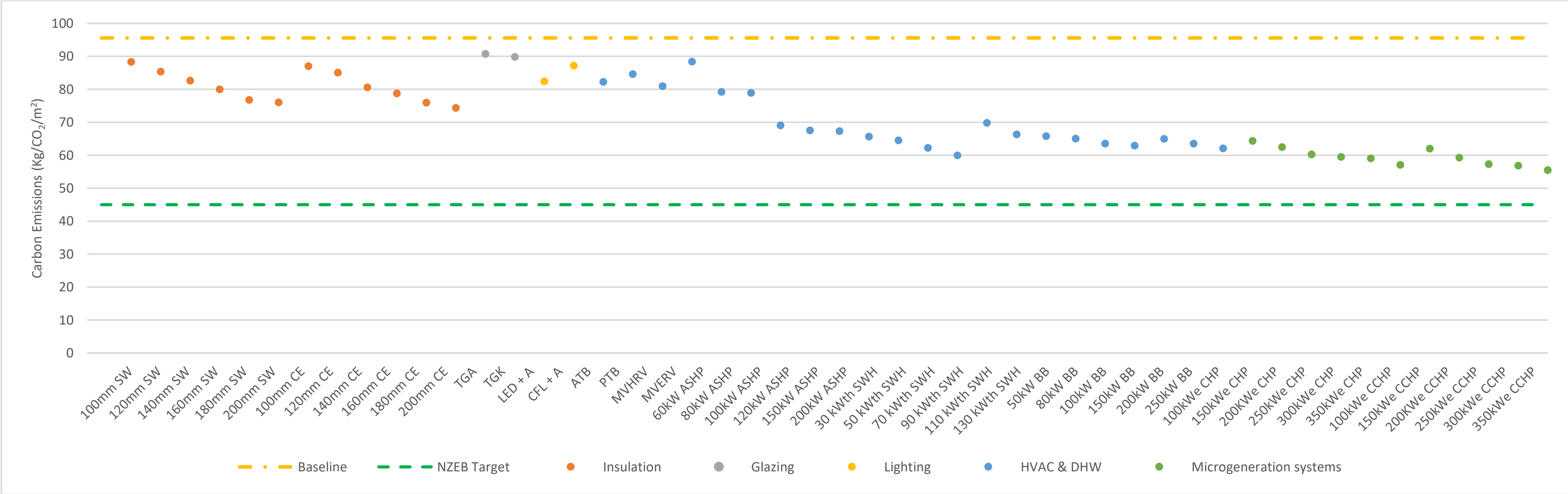


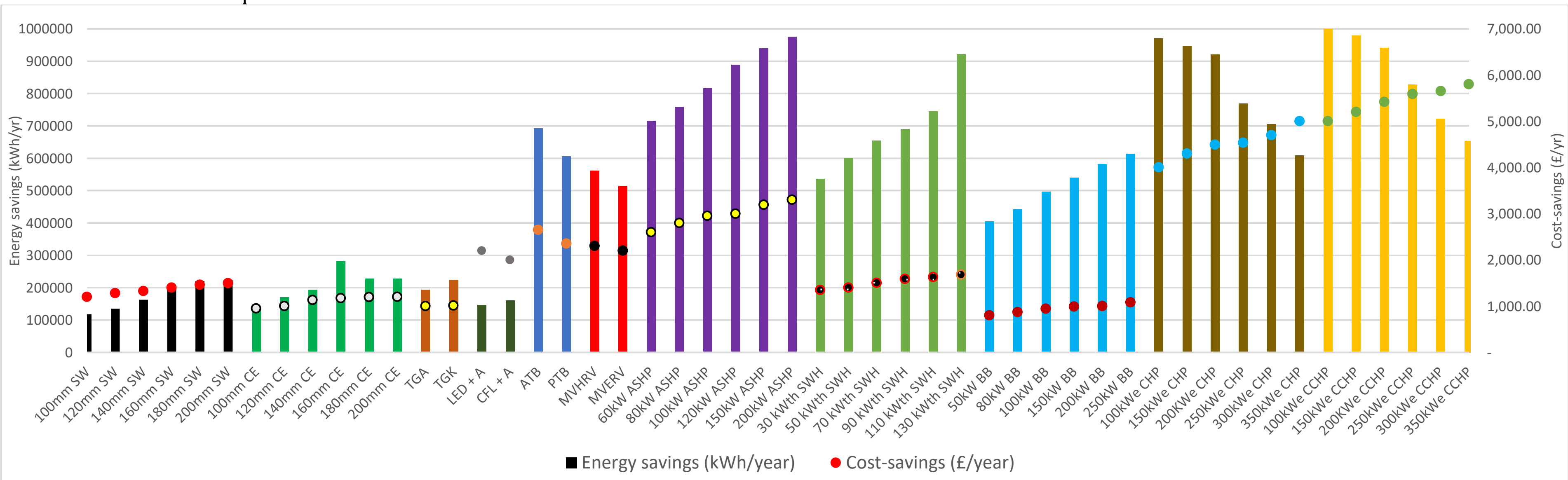
Figure 5.9a: Energy consumption with implemented measures



5.9b: Primary energy consumption of baseline model and with CHP and CCHP



5.9c: Carbon emissions with implemented measures



5.9d: Energy savings against cost-savings

Figure 5. 9: Energy consumption, PEC, carbon emissions, and energy vs cost savings of the case-study with individually implemented measures

5.3.4. Retrofit Scenarios Simulations

Figures 5.10 a-d present the energy consumption, carbon emissions, and PEC reductions achieved with a combination of 2, 3, 4 and finally all possible combinations of the EEMs in comparison to the baseline model and the nZEB target. When evaluating the reductions achieved with the different combinations of EEMs, some issues are highlighted. Firstly, achieving the nZEB target for energy consumption with a CHP unit is not possible even when other measures are incorporated. Meanwhile, the PEC and CO_2 emissions targets are easily achieved with just CHP and three additional measures. Per EPBD guidelines the nZEB definitions that have been released across Europe have only focussed on setting the PEC as the main indicator for residential and commercial nZEBs. Correspondingly, across the literature, nZEB retrofit studies have also focussed on lowering the PEC of a case-study building to meet their respective targets. Therefore, not achieving the nZEB target for energy consumption due to the incorporation of CHP should not undermine its benefits and main advantage: drastically lowering the PEC. However, where an official definition is released, and it stipulates a certain level for energy consumption, then a renewable measure such as the SWH would have been a viable option to lower and meet the target despite the lower cost-savings to be achieved with this option.

Generally, the results suggest that to achieve the nZEB target a renewable/microgeneration system is essential. Even when a combination of insulation, glazing, lighting, and mechanical ventilation is implemented on the building they are unable to lower any of the indicators to the required target.

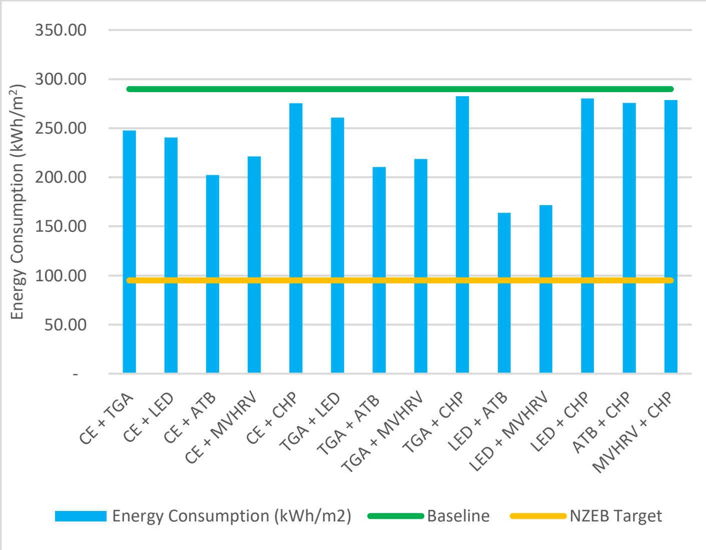
The main conclusion to be drawn from Figure 5.10 is that the nZEB target is not achievable just by incorporating two EEMs. A combination of CHP and LED managed to reduce the CO_2 emissions to just meet the target and CHP and ATB resulted in the largest reduction in PEC. Combining insulation and glazing resulted in the smallest reductions for all indicators, making it the least favourable combination. On the other hand, the combination of LED and ATB resulted in the best average savings across the indicators.

Similarly, a combination of three measures does not meet the nZEB target for energy consumption or PEC and the CO_2 emissions target is only achieved when CHP is one of the EEMs being trialled. Implementing lighting, a HVAC/DHW measure, and CHP together contributed to the largest reductions for the indicators. Meanwhile, combining insulation, glazing, and lighting is the least favourable combination. It is also observed that a combination of insulation or glazing separately with 2 other EEMs outperformed the combination of insulation, glazing, and any other measure.

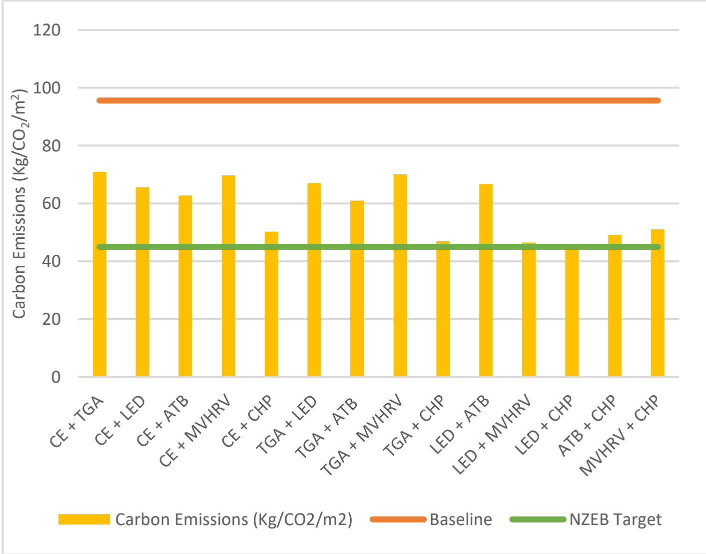
Figure 5.10 highlights that combining four EEMs is enough to reduce the CO_2 emissions and PEC to meet the nZEB target; however, once again the incorporation of CHP is necessary. The combinations of EEMs which did not include CHP performed best at reducing the energy consumption. Nevertheless, as discussed earlier because nZEB targets focus on reducing the PEC and CO_2 emissions to a certain level using these two indicators as the criterion as to whether the building met the nZEB target is satisfactory. It is apparent that the combinations of EEMs with insulation outperformed the exact same combinations but with glazing incorporated instead. Therefore, the incorporation of insulation, lighting, HVAC/DHW, and CHP offered the biggest reductions.

Implementing all the different combination of EEMs together on the building did not lead to additional significant savings in any of the three indicators. In fact, the PEC and CO_2 emission reductions achieved with all the EEMs being incorporated in comparison to a combination of four EEMs is less than 12%. The main reason for this is because the combination of all measures together meant adding insulation and glazing which did not result in substantial reductions. The energy consumption however benefits the most from the incorporation of all the measures.

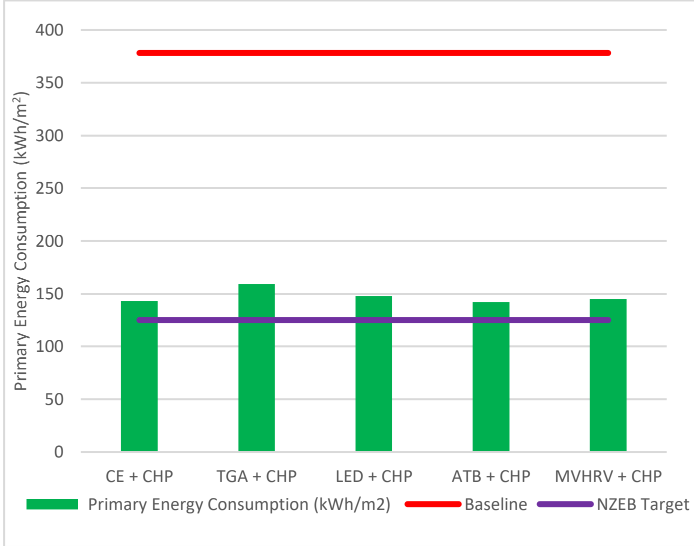
Nonetheless, reaching the nZEB target without improving the insulation and/or glazing is not possible. The implementation of insulation/glazing provides a necessary reduction in the space heating demand of the building. Although improving HVAC/DHW equipment individually contributed to significant reductions for all three indicators, when combined with other EEMs their contribution subsides. This, in addition to their energy-cost-saving balance, presented earlier, suggests that improving HVAC/DHW equipment should be one of the final solutions to consider after all other options have been explored.



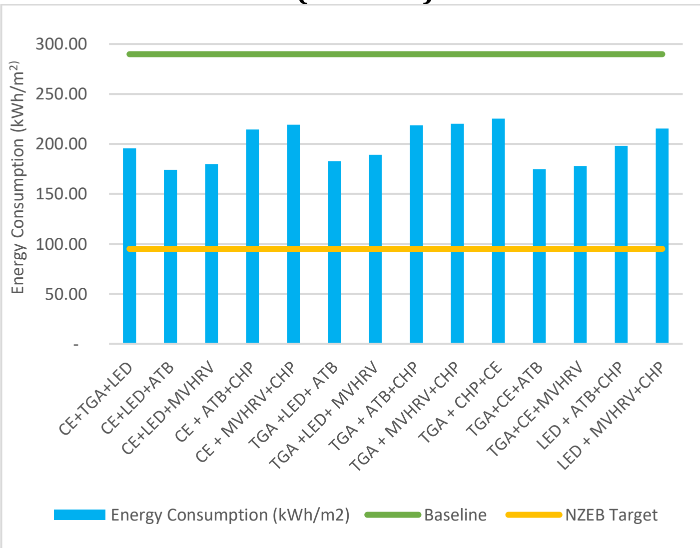
(5.10 - 1a)



(5.10 - 1b)



(5.10 - 1c)



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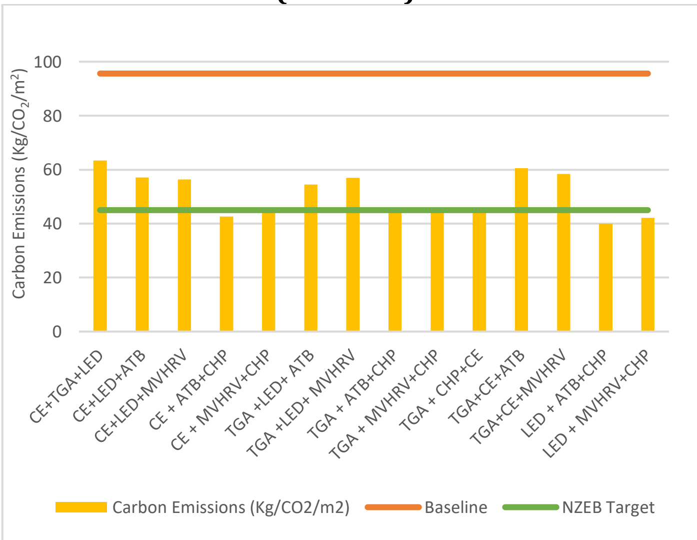

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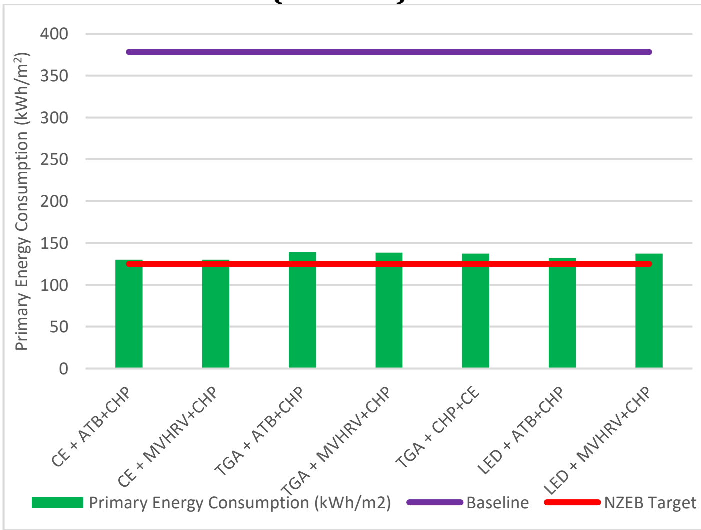

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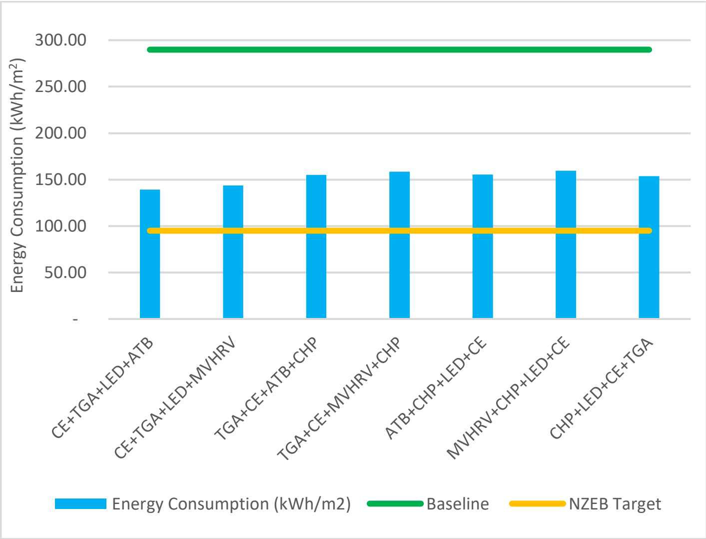
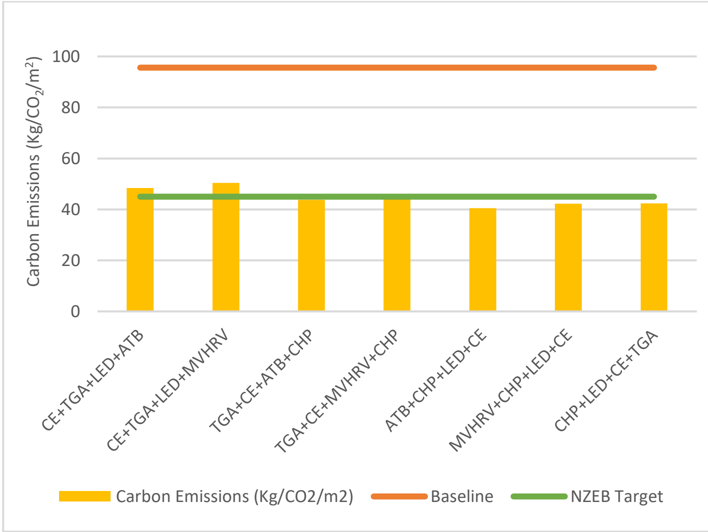
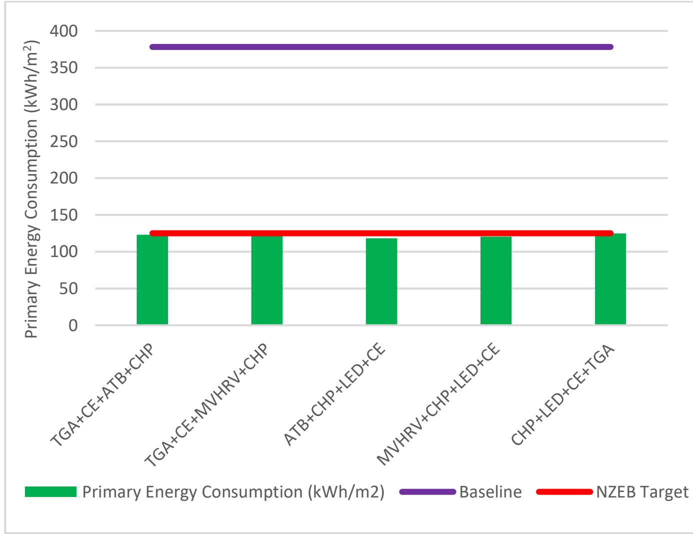


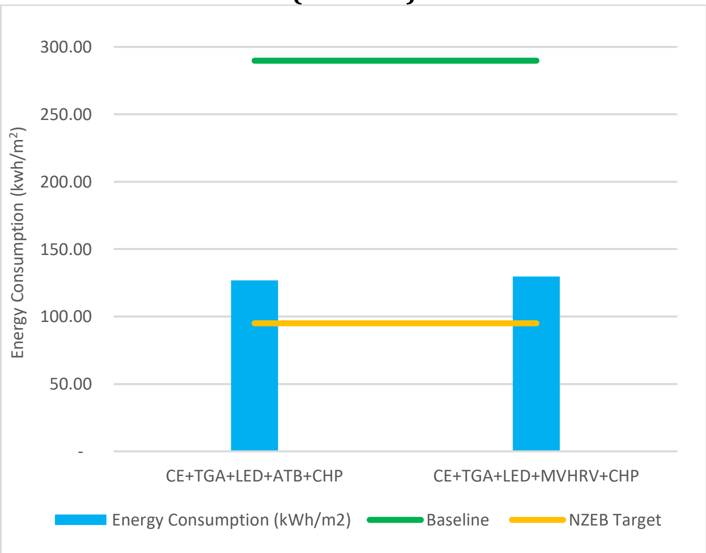
(5.10 - 3a)



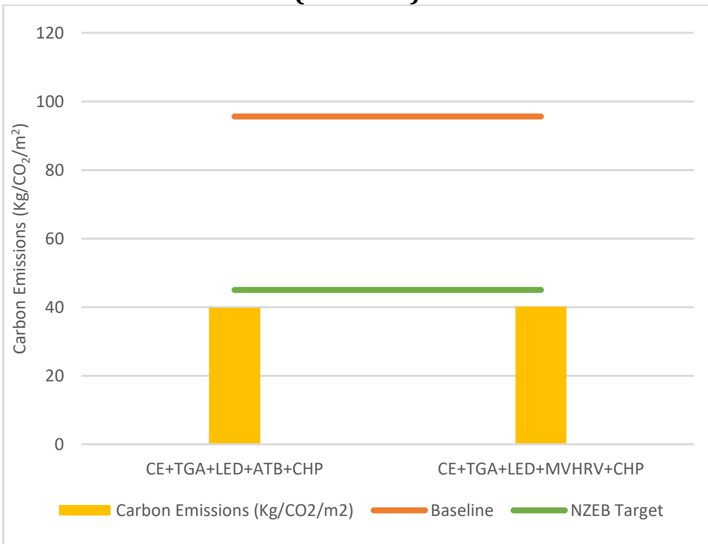
(5.10 - 3b)



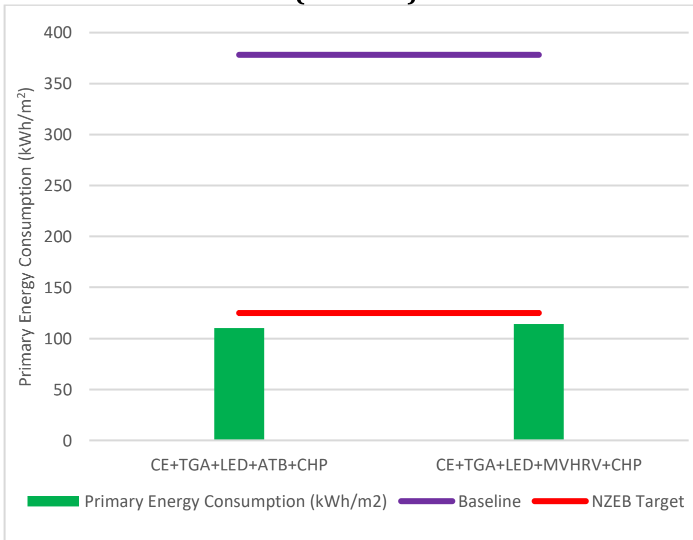
(5.10 - 3c)



(5.10 - 4a)



(5.10 - 4b)



(5.10 - 4c)

Figure 5. 10: (a) Energy consumption (b) Carbon emissions and (c) primary energy consumption with a combination of 2, 3, 4, and 5 EEMs against baseline model and NZEB target.

5.4. Summary and Conclusions

This section presented the application of dynamic thermal analysis simulation to evaluate the energy performance of Hilton Edinburgh Grosvenor hotel and whether reaching the nZEB standard is feasible for older buildings. A performance gap of less than 5% was achieved. The evaluation considered the effect of individually implementing various EEMs. Once the final selection of EEMs was decided upon based on the initial results, the EEMs were systematically combined to see which combination of EEMs work best together and lower the energy consumption, CO_2 emissions, and PEC to meet the nZEB target.

Examining the impact of incorporating different EEMs it is apparent that certain measures have a larger impact on the energy performance of the building. Thus, the following conclusions can be drawn:

To achieve the nZEB standard a combination of at least four EEMs is required. Most importantly, a renewable or microgeneration measure must be one of those measures.

nZEB energy performance is achievable with low and high levels of insulation. Similarly, triple glazing is not necessary to meet the nZEB energy performance target. However, these measures are necessary because they were able to reduce the energy demand by an average of 15% and greatly improve the air tightness of the building. Therefore, not improving the building envelope and heat resistance of building element to lower U-values where there is room for potential improvements will mean the building is not a truly energy efficient nZEB building. However, to obtain maximum savings insulation and glazing should not both be upgraded simultaneously. Instead, based on the existing building fabric and elements of the building envelope either insulation or glazing should be improved. This is particularly true for commercial buildings which tend to be retrofitted more often to ensure occupant comfort and therefore usually already have adequate insulation or glazing.

Improving and/or installing DHW/HVAC equipment does yield significant energy savings, however the cost-savings were very minor in comparison. In addition, whilst the implementation of insulation/glazing provides a necessary reduction in the space heating demand of the building, incorporating HVAC/DHW measures simply optimises energy consumption. The exception to this is where the measure being incorporated is a renewable measure such as SWH or an air/ground source heat pump. However, these measures underperformed when compared to the microgeneration systems.

It should be noted that recent fluctuations in weather conditions and unprecedented extremes does not only refer to colder weather conditions, but also increased number of heatwaves. In this case the focus on improving the building envelope and its components may prove to be counter-intuitive and increase risk of overheating. Therefore, whilst thermal comfort may be achieved during colder months, it is also possible that during the hotter months overheating and thermal discomfort occurs. Under these uncertain weather conditions, investing in improving HVAC equipment and artificially achieving a balance between the heating and cooling energy needs may prove to be the best solution.

To ensure lighting related energy consumption is optimised in a cost-effective way, an automatic presence detector is a viable solution. Although these can only be used in certain public areas of hotels to ensure occupant comfort, they have significant energy and cost savings. Furthermore, they worked very well to reduce the energy consumption and CO_2 emissions when combined with any other measures. The true potential of this measure however may only be realised in a different application such as an office or educational building type where they can be utilised in most areas.

5.5. Case study 3

5.5.1. Building Description

The final selected commercial case study is Hilton Watford hotel located in Elton Way, Watford. It is a purpose-built hotel constructed in the early 1990s. This case study was selected as it is representative of the typical construction traditions of UK hotel buildings. The hotel building is spread mainly over two floors. It is constructed of traditional bricks, a flat roof, and double-glazed windows [see Table 5.2 for further detail]. The building core occupancy hours are 24 hours, 7days a week due to the nature of the business. The total building floor area is 10,695m^2 and 2,825m^2 of conditioned floor space.

The building is cooled by one main chiller, direct expansion (DX) air conditioning units, variable refrigerant flow (VRF) systems, and multi single/ multi split systems. The systems provide cooling to restaurant/bar, conference suites, TV Comms room, lift motor room, meeting rooms, gym, leisure clubs, and back of office areas, along with three air handling units supplying and extracting fresh air across various areas. The terminal units used within site are linear supply air diffusers, fan coil units, ducted units, ceiling cassettes, and wall mounted units. The systems are controlled via one main building management system, hard wired controllers, and individual remote controllers. The total installed cooling capacity is 490kW.

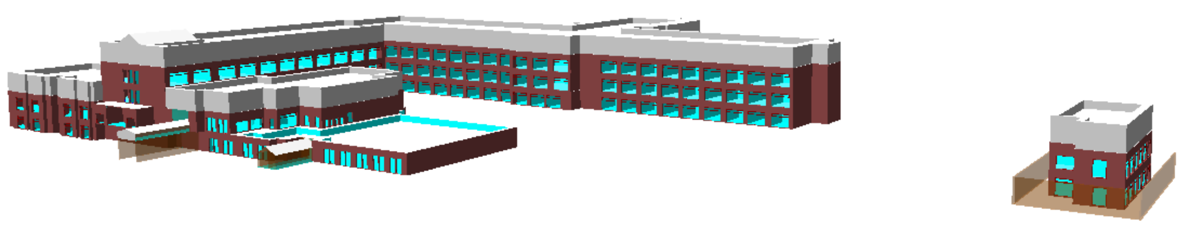


Figure 5. 11: 3D model of the case study building

Table 5.2: summary of case study and modelling process

Use: Commercial		
Building fabric	***Type***	Traditional build[1] including block, bricks, and precast units (stair-case and slabs)
Occupancy rate		24/7
Wall (calculated area weighted average u-values)	***U-value (W/m²K)***	0.45
Roof (calculated area weighted average u-values)	***Type***	Flat - Single-Ply Membrane
	U-value (W/m²K)	0.35
Floor (calculated area weighted average u-values)	***Type***	Ground & first floor: cast concrete slab Other floors: precast slab
	U-value (W/m²K)	0.35
Windows (calculated area weighted average u-values)	***Type***	Double glazing (air-filled)
	U-value (W/m²K)	2.0
Zone - occupancy levels, people density, lux level	***NCM constructions database -v5.2.tcd***	Car Park – 0.0059 person/m^2, 100 lux Bedroom - 0.094 person/m^2, 100 lux Toilet - 0.1188 person/m^2, 200 lux Reception - 0.105 person/m^2, 200 lux Hall - 0.183 person/m^2, 300 lux Food prep/ kitchen- 0.108 person/m^2, 500 lux Eat/Drink area - 0.2 person/m^2, 150 lux Circulation - 0.115 person/m^2, 100 lux Store- 0.11 person/m^2, 50 lux Laundry - 0.12 person/m^2, 300 lux Changing room – 0.112 person/m^2, 100 lux Plant room 0.11 person/m^2, 50 lux Office – 0.106 person/m^2, 400 lux Meeting room – 0.094 person/m^2, 100 lux
Air permeability		7 m^3/h/m^2 @50Pa
Infiltration		0.500 ACH
Lighting Efficiency		5.2 W/m^2 per 100 lux
Fuel Source		Natural Gas – CO_2 Factor – 0.198 Kg/kWh
		Grid Electricity – CO_2 Factor – 0.4121 Kg/kWh
Orientation		Latitude: 51.6653; Longitude -0.3609°W; +0.0 UTC
Weather data		TRY (Cibse) for London. Includes: dry bulb temperature (°C); wet bulb temperature (°C); atmospheric pressure (hPa); global solar irradiation (W·h/m^2); diffuse solar irradiation (W·h/m^2); cloud cover (oktas); wind speed (knots); wind direction (degrees clockwise from North); and Present Weather Code.
[1] refers to brickwork and blockwork constructions (walling is of masonry construction and tied with stainless steel ties to an outer leaf of block/brick)		

5.5.2.EEMs Selection

TasGenOpt was utilised to select the EEMs and retrofit scenarios [Karaguzel 2014; Hasan et al. 2008; Salem et al 2020b]. The retrofit packages are split into four categories, as shown in Table 5.3. Table 5.4 is showing the list of individual EEMs that have been selected to aggregate the retrofit packages for this hotel. Overall, the individually considered measures formed <190 nZEB retrofit packages. In total there are 46 nZEB retrofit packages for each set and they have been labelled as EP1.1-EP1.46 [see Figure 5.13]. Each EEM has been defined by its own individual code such as "ig 1.0". Selecting which EEM to consider is a critical step of the retrofit process as the selection of unsuitable measures that are incompatible with the energy needs of the building can lead to the aggregation of unsuitably large and expensive packages.

The investment costs are obtained from various UK databases that provide figures for the retrofit of commercial buildings. The absence of an official database means it is only possible that figures are obtained from various databases. Studies and reports have highlighted that there needs to be "an approved products and suppliers list for commercial property retrofit" [Dixon, 2014]

The specification of the EEMs is defined by the parameters shown in the last column. The parameters are selected so that they exceed the nZEB target by no more than 20% [≤20%]. For example, where a wall U-value ≤ 0.15 W/m^{2}K is stated, all the wall insulation EEMs will have a U-value less than or equal to 0.15 W/m^{2}K (depending on the specific material and thickness). This variation is included so that there is also a variation in the energy performance and costs, and therefore LCCs. This in turn offers a range of different and possibly more cost-effective solutions. The relevant system efficiencies are also included in that column. The main areas of retrofit considerations are thermal insulation, glazing, lighting, heating, ventilation, cooling, DHW, and incorporating a renewable/microgeneration system.

Table 5. 3: Description of the four categories that make up the retrofit packages

Set	Description	Example
1	Significant fabric and lighting improvements, assisted by little improvements to HVAC and undersized renewable/ microgeneration systems	Ig3.5 + ig6.3 + L3.0 + Hd4.0 + rm3.0
2	Significant HVAC improvements, assisted by little fabric and lighting improvements and undersized renewable/ microgeneration systems	Ig1.0 + L2.0 + Hd3.0 + Hd4.0 + rm4.0
3	All-round retrofit i.e. selective fabric, lighting, HVAC and renewable/ microgeneration systems	Ig2.4 + ig6.1+ L1.0 + Hd2.0 + Hd4.1 + rm2.4
4	Small fabric and lighting improvements, assisted by significant HVAC improvements and renewable/ microgeneration systems	Ig2.0 + L1.0 + Hd1.0 + Hd4.0 + rm5.5

Table 5. 4: Summary of the individual EEMs utilised

Areas of retrofit	Code	EEM Description	Investment cost		Parameter(s) & System efficiencies
			Unit	Cost	
1. Insulation & Glazing	ig1.0	Rigid polyurethane foam (PUR), 50mm, 2in	**£/m²**	30	U-value of wall ≤ 0.15 W/m²K U-value of floor ≤ 0.15W/m²K U-value of Roof ≤ 0.20 W/m²K U-value of windows ≤ 1.20 W/m²k Air permeability rate ≤ 2.5 m3/h/m2 @50Pa
	ig1.1	PUR, 60mm, 2in		37	
	ig1.2	PUR, 70mm, 2in		45	
	ig1.3	PUR, 80mm, 4in		55	
	ig1.4	PUR, 90mm, 4in		60	
	ig1.5	PUR, 100mm, 4in		72	
	ig2.0	Polyisocyanurate (PIR), 50mm	**£/m²**	30	
	ig2.1	PIR, 60mm		35	
	ig2.2	PIR, 70mm		46	
	ig2.3	PIR, 80mm		58	
	ig2.4	PIR, 90mm		63	
	ig2.5	PIR, 110mm		71	
	Ig3.0	Rigid thermoset phenolic 25mm	**£/m²**	35	
	Ig3.1	Phenolic foam, 30mm		46	
	Ig3.2	Phenolic foam, 35mm		55	
	Ig3.3	Phenolic foam, 40mm		67	
	Ig3.4	Phenolic foam, 45mm		75	
	Ig3.5	Phenolic foam, 50mm		83	
	Ig4.0	Glass wool, 140mm	**£/m²**	33	
	Ig4.1	Glass wool, 180mm		46	
	Ig4.2	Glass wool, 200mm		54	
	Ig4.1	Glass wool, 240mm		66	
	Ig4.4	Glass wool, 280mm		74	

	Ig4.5	Glass wool, 300mm		80	
	Ig5.0	Mineral Wool, 140mm	**£/m²**	37	
	Ig5.1	Mineral Wool, 180mm		48	
	Ig5.2	Mineral Wool, 200mm		57	
	Ig5.3	Mineral Wool, 240mm		68	
	Ig5.4	Mineral Wool, 280mm		77	
	Ig5.5	Mineral Wool, 300mm		85	
	Ig6.0	Triple Glazing, 42 mm Air filled	**£/m²**	350	
	Ig6.1	Triple Glazing, 42 mm Air filled, Low-e		478	
	Ig6.2	Triple Glazing, 42 mm Krypton filled, Low-e		560	
	Ig6.3	Triple Glazing, 42 mm Argon filled, Low-e		690	
2. Lighting	L1.0	LED (Light emitting diode)	**£/m²**	45	Efficacy min ≤ 80 lm/W
	L2.0	CFL (compact fluorescent)		35	
	L3.0	LED + auto presence detection		165	
	L4.0	CFL + auto presence detection		145	
3. HVAC/DHW	Hd1.0	200kW High efficiency biomass boiler	**£/kW**	900	Biomass Boiler – 85% efficient MVHR -Specific fan power = 0.5 & heat recover efficiency = 90%
	Hd2.0	Automatic split heat pump system		450	
	Hd2.1	Heat pump variable refrigerant flow		720	
	Hd2.2	Programmable split heat pump system		780	
	Hd3.0	Auto. thermostat controlled direct gas fired Boiler		590	
	Hd3.1	Programmable Thermostat direct gas fired Boiler		500	
	Hd4.0	Mechanical ventilation with heat recovery		350	
	Hd4.1	Mechanical ventilation with energy recovery		460	
4. Renewable/ Microgeneration systems	rm1.0	150kWe Combined heat and power [CHP]	**£/kW**	850	SWH – Zero loss collector efficiency = 0.81; heat loss coefficient = 3.9 ASHP – Coefficient of performance (CoP) 3 GSHP – CoP 3 PV > 15% efficient CHP – 37% elec. efficiency & 47% heat efficiency CCHP – 17% elec. efficiency & 60% heat efficiency
	rm1.1	200kWe CHP		1200	
	rm1.2	250kWe CHP		1800	
	rm1.3	300kWe CHP		2500	
	rm1.4	350kWe CHP		3400	
	rm1.5	400kWe CHP		4000	
	rm2.0	150kWe Combined cooling heat and power [CCHP]	**£/kW**	2000	
	rm2.1	200kWe CCHP		2600	
	rm2.2	250kWe CCHP		3300	
	rm2.3	300kWe CCHP		4000	
	rm2.4	350kWe CCHP		4700	
	rm2.5	400kWe CCHP		5300	
	rm3.0	20kW Monocrystalline photovoltaic [PV] Panels	**£/m²**	400	
	rm3.1	30kW PV Panels		460	
	rm3.2	40kW PV Panels		540	
	rm3.3	50kW PV Panels		630	
	rm3.4	80kW PV Panels		740	
	rm3.5	100kW PV Panels		850	
	rm3.6	50kW PV with storage		780	

	rm4.0	35kWth Solar water heating- flat plate collectors [SWH]	**£/m²**	420	
	rm4.1	55kWth SWH		500	
	rm4.2	75kWth SWH		580	
	rm4.3	95kWth SWH		660	
	rm4.4	115kWth SWH		750	
	rm4.4	125kWth SWH		870	
	rm5.0	70kW Air source heat pump [ASHP]	**£/kW**	1300	
	rm5.1	80kW ASHP		1370	
	rm5.2	100kW ASHP		1440	
	rm5.3	120kW ASHP		1490	
	rm5.4	145kW ASHP		1570	
	rm5.5	150kW ASHP		1600	
	rm6.0	60kW Ground source heat pump [GSHP]	**£/kW**	1500	
	rm6.1	70kW GSHP		1580	
	rm6.2	80kW GSHP		1640	
	rm6.3	100kW GSHP		1690	
	rm6.4	120kW GSHP		1730	
	rm6.5	140kW GSHP		1770	
Type of Building: Commercial **Costs are collected from: BEIS, 2016; UK 2050 calculator -2050 Pathways [GOVUK, 2019]** **Electricity cost (pence/kWh): 12.9 [Hilton]** **Natural gas cost (pence/kWh): 2.8 [Hilton]**					

5.5.3.Baseline Model Validation

To evaluate the difference in energy performance before and after retrofit, the first step is to analyse the baseline model and validate that it is a true representation of the actual building. To validate the baseline model created on Tas, the simulated energy consumption value is compared against the building's actual energy consumption. As mentioned previously the site survey enables the development of a thorough model that reproduces all the characteristics and systems of the building as it currently stands.

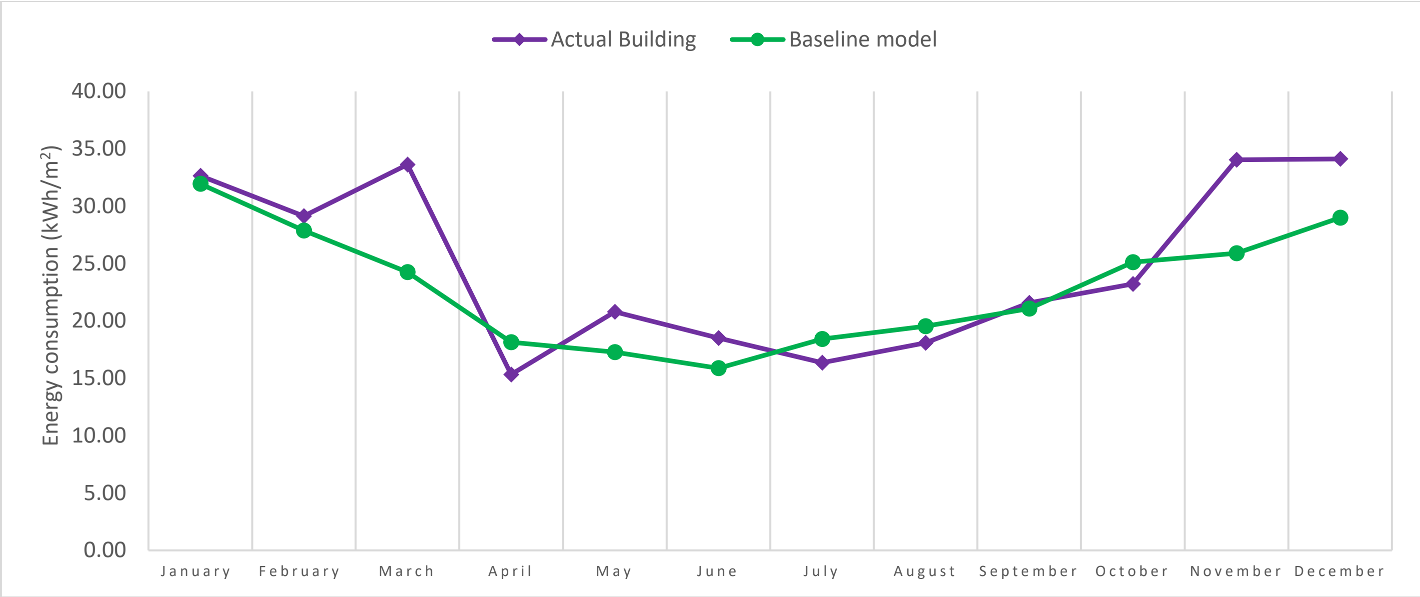
Looking at Figure 5.12 there is an 8% difference in energy consumption between the model and the actual energy consumption. This 8% is an underestimation of the actual energy consumption of the hotel. However, as discussed throughout this thesis the performance gap cannot be completely closed now [Knight, Strvoravdis and Lasvaux 2008, Guceyeter and Gunaydin 2012, Collins 2012]. Several complexities exist, especially the occupant's behaviour, which cannot be entirely assumed.

Furthermore, the weather data used in simulation studies will never replicate the microclimate of the building's location and it is typically not representative of a specific and real year but is based on averages, as discussed earlier. As a result, despite the high quality of input data used to develop the model it is reasonable that there remains a difference between simulated and actual energy consumption.

Looking at the energy profile for the actual energy consumption, there are unusual fluctuations in the energy consumption during certain months. The reason for this anomalous profile is due to the year that is selected. During 2018 the UK had uncharacteristically low temperatures and snow during February/March. Following this, a heatwave occurred during April and some of the warmest days on record were experienced [BBC news, 2018; Telegraph, 2018].

However, when the annual energy consumption of the year 2018 is compared to the annual energy consumption of the previous 2 years, it is discovered that the difference in the total annual energy consumption between the 3 years is negligible (<5%).

Consequently, it did not matter which year is utilised to compare against as it did not have a significant effect on the results or the validation of the model. This, however, suggests that the hotel's current energy consumption is affected by other factors and activities that are not weather dependant and that the hotel's energy management could be improved upon. A full climate control system is not included as part of the investigated EEMs because the benefits of such a system largely depends on occupant behaviour. Therefore, in a hotel setting it can only be utilised in certain public areas as guest comfort would always be a priority.



$$Percentage\ error = \left(\frac{274.97 - 297.41}{274.97}\right) * x100 = -8\%$$

$$* \ Unit: (kWh/m^2)$$

Figure 5. 12: Comparison of the actual energy consumption (2018) against the modelled annual energy consumption

5.5.4.Energy Performance Analysis

Figures 4 and 5 show how the performance of the model varies in comparison to the nZEB target and relative to the baseline building. Between the four sets of packages there are clear differences in how they affect the energy performance of the hotel building. All the packages proved to be successful at meeting the carbon emissions target.

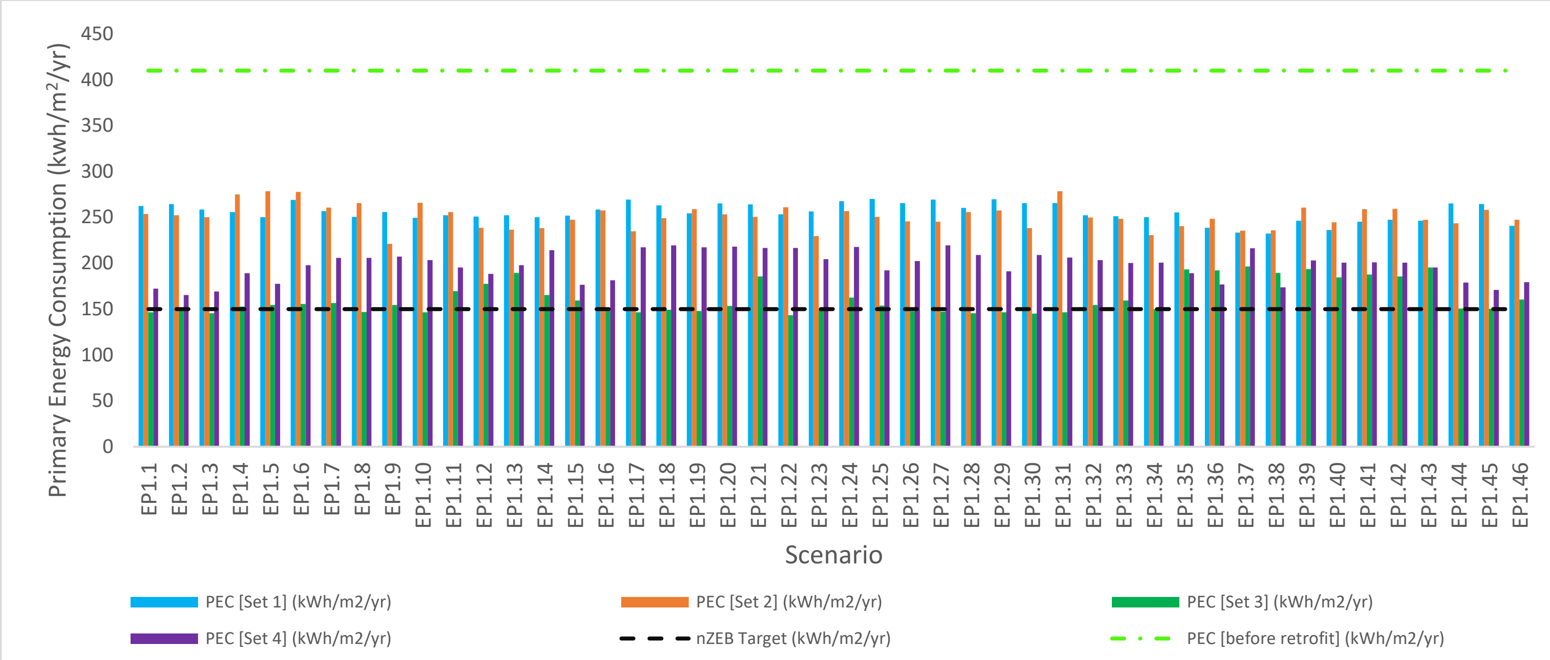
'Set 3' ensured that all the nZEB targets are met by incorporating that most suitable EEMs i.e. selective fabric, lighting, HVAC, and renewable/ microgeneration systems. The packages within 'Set 3' can easily be considered the 'best performing' set of packages. This is demonstrated by Figure 5.13, which shows a significant difference in the PEC between the four different sets. The average percentage difference between the packages within 'Set 3' and 'Sets 1 and 2' is a considerable 44%.

'Set 4' is comprised of packages that had small fabric and lighting improvements, assisted by significant HVAC improvements and renewable/ microgeneration systems. The retrofit packages within this set led to very similar results to that of 'Set 3'. On average packages within this set performed better than packages within 'Sets 1 and 2' by 17%. Within this set, packages that incorporated SWH and PV did not work well to reduce the PEC. This is because these measures do not meet the significant heating and cooling energy needs of the hotel. This highlights the importance of incorporating not just any renewable/microgeneration system but selection of the most suitable system that meets the energy demands of the building being retrofitted.

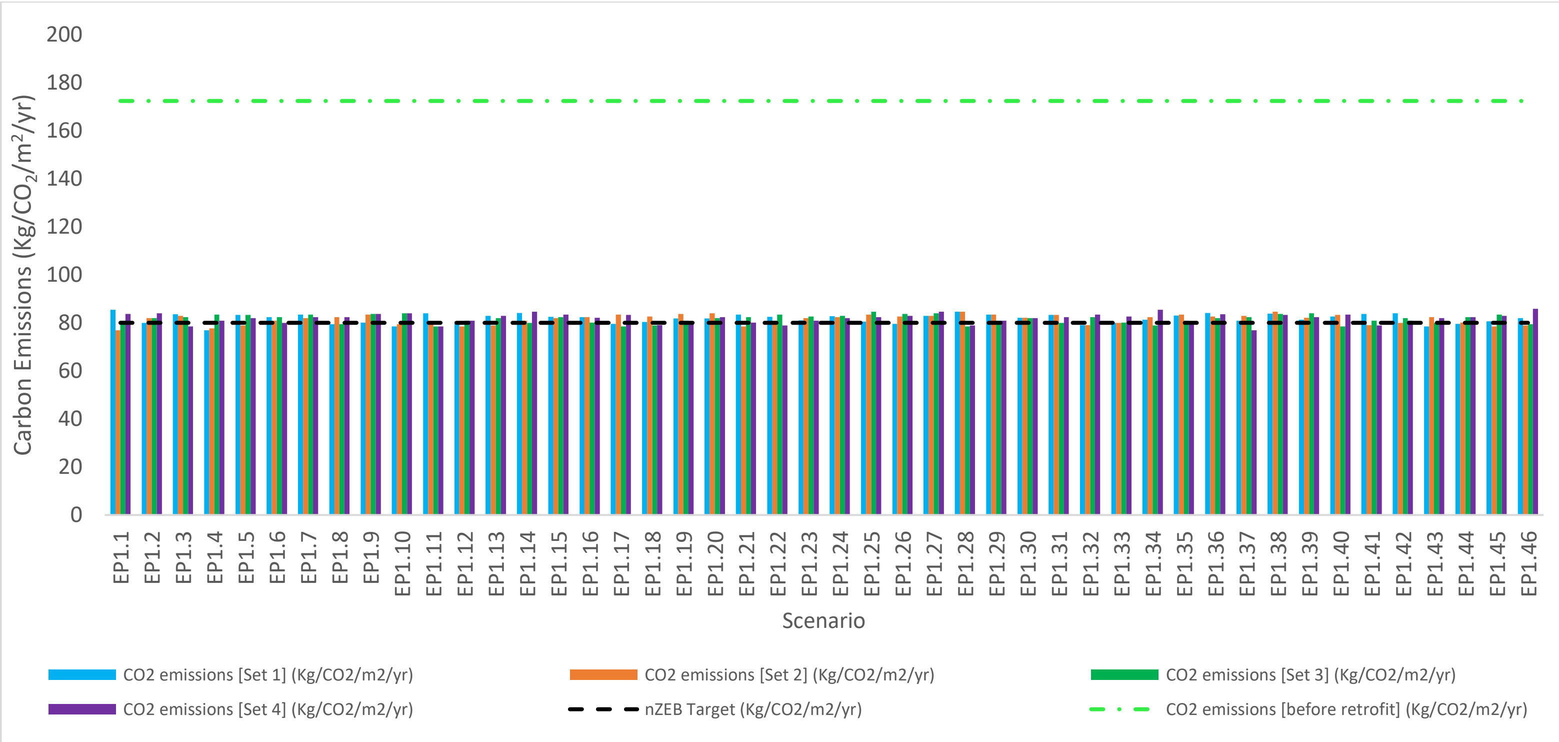
Furthermore, although 'Set 4' performed very well in terms of reducing the PEC, the packages within this set did not meet the all the nZEB requirements. In general, the packages are successful at lowering the PEC and carbon emissions. However, not all packages are able to meet the envelope requirements which means that the energy demand of the building is not lowered to the nZEB standard.

Interestingly, 'Set 1,' which is comprised of packages with significant fabric and lighting improvements had very little/no variation in terms of energy performance. Regardless of which HVAC and renewable/microgeneration system is incorporated as part of the package, the PEC remained mostly unaffected. Packages within 'Set 2' produced very similar results to that of 'Set 1.' In general, packages within 'Set 1' and 'Set 2' underperformed in comparison to the packages in the other two sets. 'Sets 1 and 2' highlight the importance of incorporating an adequately sized renewable/ microgeneration system. The packages within these sets have similar investment costs to those of the other sets and despite this the nZEB target could not be met. This also has an impact on the operational costs and therefore LCCs. If the packages do not successfully reduce the PEC and therefore energy costs, then the investment cannot be justified.

In terms of CO_2 reductions, all packages were able to meet the nZEB emissions target. Even with an undersized renewable/microgeneration systems packages within 'Set 1 and 2' were able to reach the required target. This suggests that fabric improvements and systems optimisation can be as important to reducing building emissions as renewable systems. The average percentage decrease in emissions between all sets was 53%.



(a)



(b)

Figure 5. 13: Comparison of the (a) primary energy consumption and (b) carbon emissions for the case study building before and after retrofit and the nZEB target

5.5.5. Global Cost Analysis

The cost-optimal solution should ideally represent the best combination of the energy and cost performance. A balance between the two is necessary. A focus on just lowering the costs means the nZEB requirements are not met. Likewise, a focus on just meeting the nZEB standard with the current level and cost of technology renders the solution economically unfeasible. Figure 5.14 is showing the PEC of all the packages against the global costs, the cost optimal range, and the nZEB target.

Certain packages did not meet the nZEB target at all. There is a clear distinction between the packages that made up the four different sets. Packages within 'Set 1 and 4' resulted in the highest global costs in comparison to the other two sets. Whilst majority of packages in set four met and exceeded the nZEB standard, the same is not true for packages in 'Set 1.' In fact, despite having the highest global costs, none of the packages in 'Set 1' met the nZEB target. As a result, the energy benefits gained by focussing on significant building fabric and lighting improvements is not justified by the associated global costs.

Packages within 'Set 2 and 3' also performed similarly in terms of their cost performance. However, 'Set three' had the lowest global costs on average in comparison to all the other sets. This highlights the importance of selecting a variety of EEMs that meet the building's energy demand, rather than focussing on one retrofit aspect and working around that.

The cost-optimal primary energy consumption value is 193.59kWh/m^2/yr as obtained from the cost-optimal graph shown in Figure 5.14. The nZEB target's primary energy consumption level is 150kWh/m^2/yr. This 30% percent gap between the cost-optimal solution and the nZEB target is significant. However, considering the fact that the cost-optimal solution offered a reduction of 52% and 45% in primary energy consumption and global costs in comparison to the baseline scenario it can be said that it is still a viable option in terms of reducing the energy consumption but not fully meeting the nZEB standard. Therefore, the cost-optimal solution offered a considerable reduction in both energy and costs.

It may be that with the current level and price of EEMs available, finding a balance between the energy and cost benefits is one of the best options to carrying out energy retrofits and as such technologies become widespread in use, it is always possible to carry out further, albeit minor, retrofits in the future to fully meet the required standard.

To achieve a balance between the energy and cost requirements it is best to consider alternatives of certain measures. As opposed to neglecting to address specific requirements altogether. Even small changes in the type of measure selected (e.g. selecting 80mm PIR not 110mm) can help reduce global cost. Thereby bridging the gap between the cost-optimal level and the nZEB level. In general, it can be said that it is difficult to keep the global costs to a minimum whilst ensuring that the building envelope meets the nZEB standard.

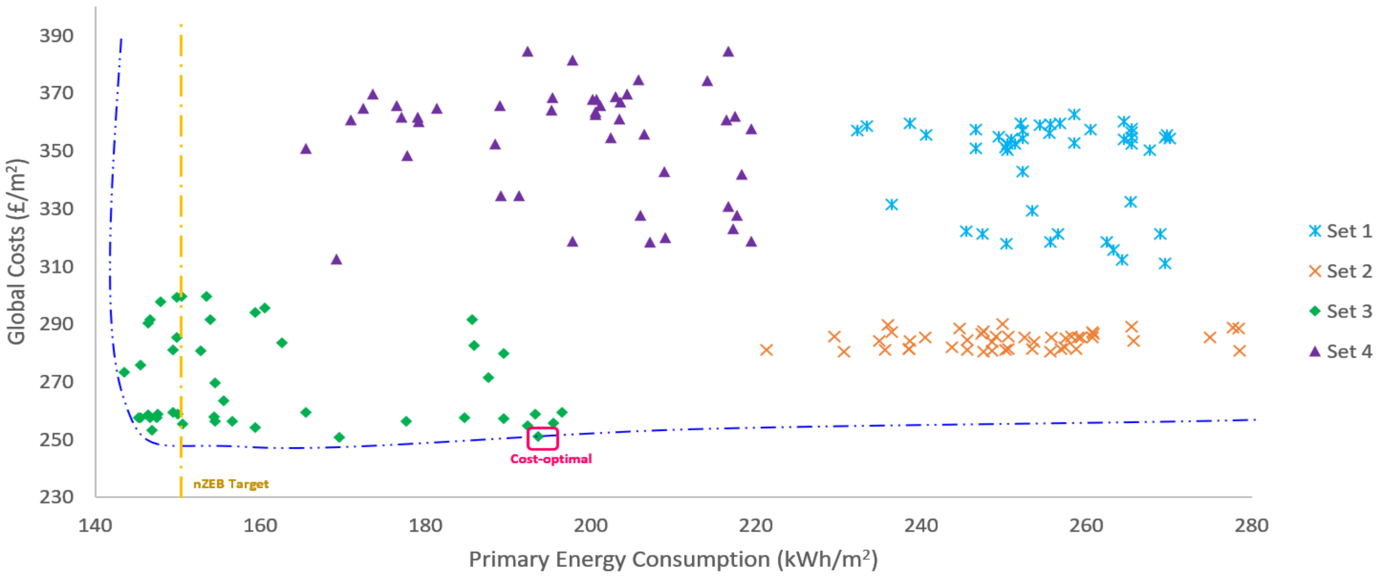


Figure 5. 14: Cost-optimal graph showing the global costs against the primary energy consumption of the different packages

5.5.6. Summary and Conclusions

The four different sets of retrofit packages assumed various priorities when grouping the EEMs and this presented some interesting results. Adopting this methodology whereby different retrofit packages focussed on different potential retrofit aspects proved that a whole-building retrofit is the best route to achieving the nZEB standard. Prioritising one aspect of retrofitting and neglecting another simply leads to an 'incomplete' retrofit that either fails in lowering the energy demand of the building or in improving the overall energy efficiency of systems and components. It is a rather simple process to achieve the energy consumption target of the 'nZEB standard' by incorporating large-scale renewables. However, this simply meets the existing high energy demand, meaning that the building is still not truly energy efficient, as highlighted by set four.

The comparison of the retrofit variants within a certain set showed the importance of selecting not just a range of EEMs that work together to meet the standard but rather a range of 'suitable' EEMs. Suitability always depends on the baseline building and its current energy demand and usage. For example, for this case study the most compatible renewable/microgeneration measures were ones that offered a balance between the heating and cooling needs during the heating and non-heating season. As a result, measures that only focussed on meeting the heating needs underperformed at reducing the PEC.

To bridge the gap between the nZEB solution and the cost-optimal one certain trade-offs may be necessary. However, one of the simplest and most effective ways to do this would be by increasing government incentives so that there is an increase in the private interest gained and therefore the public value to further encourage the uptake of such a large investment. A natural incentive to carrying out such retrofit projects is the increase in the real estate value of the building due to the volumetric additions, potential increase to occupancy rates, decease in operational costs, and aesthetic value. This is going to appeal to smaller building owners and landlords in the residential sector; however, it remains an important incentive that should be highlighted. Although this may also lead to a negative financial effect on the operator/ occupier of the building, if rent increases are incurred for example. Comparing the results between and within the different sets of retrofit packages demonstrates that it is also possible to reduce the global costs by finding alternative EEMs with lower investment costs.

One of the main barriers to reaching the nZEB standard is typically the large investment costs. However, buildings have their own dynamics and are not static, therefore, at certain points they always require that old components be replaced. These points should, therefore, be seen as opportunities for improvement rather than replacement. In this manner the nZEB standard may also be achieved over stages rather than at once. This notion is corroborated by other studies discussed in the literature review whereby the energy efficiency of buildings is improved by incorporating even one EEM and implementing a long-term plan for further improvements. It should be highlighted that the reduction in the PEC and global costs of 52% and 45% is achieved by incorporating a variety of EEMs. The solution provided a balance between the reduction in energy consumption and costs over the study period.

Overall, this case study demonstrated that the nZEB standard is achievable with cost benefits for a UK hotel building. The methodology utilised in this thesis can be replicated with any other commercial building. The energy validation process ensures that the results obtained are reliable. However, to increase the reliability of the cost calculation a homogeneous database for such UK retrofit projects is necessary. When this occurs, the specific cost results of such studies can be applicable to many buildings of similar stock. A comprehensive and applicable database requires several phases to be successfully utilised and will need to be defined based on location too as this can greatly affect the cost of measures.

5.6. Chapter Summary

This chapter studied 3 different hotel case studies. The case studies were all modelled, validated, and investigated to explore the various research questions set out the beginning. It presented the results and analyses and the conclusions for each investigation carried out. Based on the results, it is concluded that prioritising the improvements in energy efficiency, and then adding a renewable/microgeneration system to the building, is the best approach when retrofitting a commercial building that is located in a cold-dominant climate. In this way, thermal losses resulting from an energy-inefficient building envelope are lowered, which in turn drastically lowers the energy demand of the building. Even a historical commercial building with a listed buildings consent requirement was able to achieve the nZEB standard with this approach. To achieve a balance between energy and cost requirements, it is best to consider alternatives to certain measures. Even small changes in the type of measure selected — for example, selecting 80 mm Polyisocyanurate insulation (PIR) rather than 110 mm — can help reduce global cost, thereby bridging the gap between cost-optimal level and nZEB level. In general, it is difficult to keep global costs to a minimum whilst ensuring that the building envelope meets the nZEB standard. Overall, the presented case study demonstrates that the nZEB standard is achievable with cost benefits. The methodology utilised can be replicated with other commercial buildings. The energy-validation process ensures that the results obtained are reliable.

CHAPTER 6: NZEB FRAMEWORK

6. Chapter Introduction

The chapter ties in the investigations carried out on the different residential and commercial buildings. It begins by introducing a generic framework and then moves on to provide a detailed framework and decision matrix that aims to aid designers when it comes to retrofitting buildings to achieve the nZEB standard.

6.1. nZEB Framework

In addition to the specific design solutions that are proposed (above) for each of the various case studies explored, the generic and applicable frameworks are shown and discussed below. The frameworks are split into different frameworks and they are based on the findings of all the case studies. The aim is to provide a set of final recommendations as to which nZEB route should be taken; which building elements require focus; and which specific design variables offer the most benefit, either in terms of economic benefits or energy benefits or a combination of the two. The selection of which indicators to focus on will depend on the requirements of the investor. Furthermore, the definitions that are aggregated from the literature review are altered and finalised below. They are based on the combination of findings of the cost-optimal solutions and the nZEB ones. The main aim is to slightly alter the level of the near-zero so that the gap between technical optimality and cost optimality could be bridged.

6.2. General Framework

Each building has its own unique process and requirements. To minimise discrepancies in achieving the nZEB standard, it is necessary to form a common understanding for nZEBs among all stakeholders prior to beginning the design or retrofit process. Therefore, having an organised framework that contributes to a systematic approach for achieving the nZEB standard a common practice may be established. This can be achieved by outlining the key actions needed to ensure the achievement of energy and cost related goals. Although the overall goal always differs from one project to the next, the development of specific and measurable actions (in terms of cost and energy savings) is a critical step to ensuring that goals are truly being met, whilst following a set procedure. A framework also eliminates the potential for energy inefficient buildings, with high energy demands, to be considered 'nZEB.' The first framework presented in Figure 6.1 aims to provide a visual representation that describes the overall process and steps to be taken for all related stakeholders (from investors to designers to occupants) for all phases of achieving and later maintaining the achieved nZEB standard.

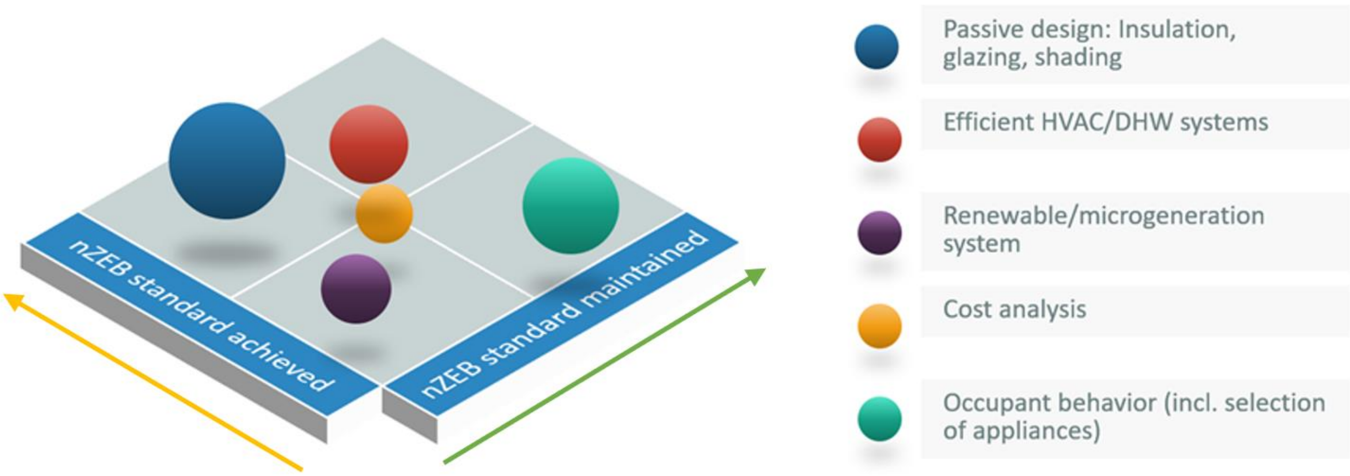


Figure 6. 1: First nZEB framework: general nZEB hierarchy

Typically, for existing buildings, the retrofitting process starts due to an issue or a factor such as failure in a building element or component; end of life of element or component; a need to upgrade the performance due to safety or new regulations; or simply because the client /landlord wants to improve their building. The figure assumes that the renovation is taking place to reach the nZEB standard. It begins by dealing with the passive design. The passive design as seen from earlier chapters can be considered the foundations of any retrofit process. A poor passive design leads to substantial energy losses through the envelope and does nothing to contribute to thermal comfort. In other words, the most efficient way to reduce the energy demand of a building is to first improve the existing passive design. This is therefore a vital step to not only achieve the nZEB standard but to assist in maintaining the standard by improving thermal comfort all year-round. The passive design does not only consider insulation and glazing but it ensures that adequate ventilation or a suitable cooling strategy is in place to keep the energy demand low during the heating and non-heating season.

Subsequently, the figure deals with optimising the HVAC and DHW of the building. Upgrading the building components and systems does not only optimise energy usage and save money, it plays a significant role in allowing occupants to maintain a comfortable temperature that is constant throughout the day and can be increased and reduced as necessary. Most importantly, thermal comfort is achieved whilst reducing the energy consumption.

Once the energy demand has been lowered and the energy usage optimised the designer can then look at incorporating energy producing measures. The size of the renewable or microgeneration system will depend on the objective of the investor and/or designer. This determines the percentage of energy consumption needing to be offset. Although such systems typically have high investment costs the long-term low operation costs combined with substantial energy savings usually mean the cost is justified. Unlike certain passive design measures which may have similar investment costs but lower energy savings in comparison, as seen in earlier chapters.

Considering the entire life cycle costs of the building is a vital part of the nZEB process. As mentioned earlier, the EPBD requires that nZEBs must have positive LCCs and if they do not then the investment is not justified, and the retrofit should not be carried out. Operation and maintenance costs typically represent the greatest expense over the lifetime of a building. The Royal Academy of Engineering provides a ration for the typical costs of operating a commercial building over 30 years: 0.1-0.5 for design costs, 1.0 for construction costs, 5 for maintenance costs and 200 for operation costs (including staff costs). Thus, to achieve a positive LCCA, it is essential that the designer focusses on incorporating measures that reduce the operation and maintenance costs (i.e. measures that control and optimise the energy usage).

Typically, the energy consumption of nZEBs is predicted or estimated during the design process. Within and outside the literature it is very rare that measurements or monitoring of the energy consumption is conducted during the operation phase of the building. This means there is no proof that the designed building is going to perform as predicted. Furthermore, there is no indication as to whether thermal comfort conditions have been achieved during both the heating and non-heating seasons. This is understandable due to the significant equipment cost and the effort and time required to monitor and analyse the collected data. However, considering the large investment costs ensuring that the achieved standard is maintained and picking up whether any part of the design needs to be slightly altered is necessary. It may also be found that it is just a matter of educating the occupants should the building not perform as predicted. Doing so would also contribute to larger cost savings in the long-term as it ensures that the calculated LCCs and payback period (which are based on the predicted operational energy use) remains true and applicable.

The above, refers to continued external energy monitoring by the designer post-occupancy until it is established that the building is performing as planned. In cases where it is not possible to do so, due to various reasons, ensuring that smart energy metering with an option for occupants to monitor their behaviour is a necessary alternative. A cost-effective and simple way to educate occupants about their energy usage and how they can reduce it would be to create online ‘lessons’ that are specific to the building and its inhabitants that can be accessed from the monitoring system application (which currently is usually available on mobile phones). In cases, where this is not possible occupants may request a desktop, emailed or printed version of this.

Table 6.2 is directly related to Figure 6.1 and discussion above. It describes the same steps taken to achieve the nZEB standard but this time with a description of the specific actions needed to achieve each step. The final (altered) nZEB targets based on the previous chapters and the discussions offered throughout this thesis are shown in Table 6.1.

Table 6. 1: Summary of nZEB targets for residential and commercial buildings

	Residential nZEB Targets	**Commercial nZEB Targets**
External wall U-value (W/m^{2}k)	0.15	0.15

Ground floor U-value (W/m²k)	0.13	0.13
Window U-value (W/m²k)	0.89	0.98
Roof U-value (W/m²k)	0.13	0.15
Air permeability rate ($m^3/h/m^2$ @50Pa)	1.0-3.0	1.0-3.0
Annual primary energy consumption (kWh/m^2)	65-75	at least 40% reduction in PEC
Annual carbon emissions ($KgCO_2/m^2$)	10	at least 50% reduction in carbon emissions

Table 6. 2: Steps to achieving the nZEB standard

Steps to achieving the nZEB standard – Applicable to: Existing Residential and Commercial buildings				
Step 1	**Step 2**	**Step 3**	**Step 4**	**Achieve: nZEB standard**
Passive design	**Building systems/components [HVAC]**	**Renewable/ microgeneration sources**	**Cost Analysis**	**Continued energy monitoring**
- Focus on improving insulation, glazing, shading -Improving this affects thermal comfort and air tightness - Average U-value for the building envelope including building elements, windows, thermal bridges etc. - it is essential that building fabric improvements are not neglected even though they may be costly. Without building fabric improvements the energy demand will not be lowered.	-HVAC system is made up of several components: AHU, heating/cooling coils, filters, attenuators, humidifiers and de-humidifiers, volume control and fire/smoke dampers, air distribution diffusers, air return grills -Look at components that will reduce energy consumption from: heating, cooling, and domestic hot water (DHW) related usage. - Improving the building fabric and increased air tightness mean some type of mechanical ventilation will be necessary.	Types include: On-site: solar, wind, geothermal, CHP, CCHP, on-site generation by off-site renewables and off- site generation by investment/production in windmills/ PV plants etc. Off-site supply: renewables in the grid *If the share of renewables in the grid is high (off-site supply), the need for new on-site and/or off-site generation will be low (and vice versa).*	- Select a variety of suitable EEMs based on the previous steps and group the measures to form several retrofit packages for comparison. - Select appropriate software to carry out a life cycle cost analysis - Gather and define all the costs associated with the project. - Investment costs are available via supplier data/ database. Fuel costs are dependent on location and supplier, operation, maintenance and replacement costs depend on existing building systems and components and the potential EEMs to be incorporated.	- Incorporate smart energy metering to allow occupants to monitor monthly energy consumption and production of energy, where applicable - Ensure that occupants can access this easily and remotely via mobile applications for example -Where possible, external energy monitoring by the designer/ project managers/ main stakeholder(s) should be undertaken

- Assess baseline building and carry out improvements where it will make a significant contribution to both energy and cost reduction, in the long-term (based on operating energy cost reduction)	- Maintenance records and existing systems must be assessed initially and any systems due to be replaced should be seen as points of improvements to both energy and cost reduction, in the long-term (based on operating energy cost reduction)-	- Carefully assess the existing layout of the building and select renewable/microgeneration systems that are compatible with this layout. Many of the currently available technologies have specific requirements for installation such as roof space, inside/outside space, nearby river/stream	- Identify what the main stakeholders (owners/landlords) aim to achieve and what their budgetary constraints are. Where possible, decisions should be mutually made. - Highlight the long-term cost savings to stakeholders to show justification for the initial high investment costs	- Monitor energy consumption and production data from the building. - Assess how the building is performing in comparison to the predicted model - Conduct surveys to figure out current occupancy behaviour and prevent the occurrence of the rebound effect
- Select insulation material - Exercise caution when selecting insulation thickness [optimise thickness]. After a certain thickness, there are no more energy benefits, thereby leading to unnecessary added costs. - Aim for a building with minimum heat losses - Ensure that it does not overheat (i.e. optimise solar gains/solar control)	-Select an efficient system that works to meet the heating and cooling needs and ensure it is energy efficient. For instance, a heat pump can be made more efficient using geothermal energy, provided ground-space is available. - Control systems should always be considered: programmable thermostats: control temperatures both during working hours and when the building is unoccupied.	- Select only suitable renewable/microgeneration systems that meet the heating and cooling needs of the building - For example, a CCHP is more suitable than PV panels in a building with constant annual heating and cooling needs. Meanwhile, PV panels would be more suited to a building with significant heating needs.	- Ensure that the main aim of a LCCA is understood by all stakeholders. A LCCA is especially useful when trying to maximise net savings. For example, it can help determine whether the incorporation of a high-performance HVAC or glazing system, which may increase initial cost but result in significantly reduced operating and maintenance costs, is cost-effective or not.	- Devise plan to educate occupants on how to monitor and alter their own energy usage habits to keep energy consumption to a minimum. - Ensure that plan is accessible to occupants and easy to comprehend and follow - If a flaw with the actual nZEB design is detected then this should be rectified by adding, taking away, or altering measures, as necessary

6.3. Decision Matrix

According to the EPBD 'renovation' of a building means an improvement of the energy performance, as opposed to just a replacement or upgrade of a single element or multiple parts of a building. A simple or minor renovation is classified as renovation involving a single measure and contributing to energy savings of up to 30% (such as the installation of a new boiler). Another level of renovation has been defined as moderate renovation and this involves renovating three to five building elements and contributing to energy savings more than 30%. The EPBD introduced the concept of 'deep renovation' and defined it as "refurbishment that reduces both the delivered and the final energy consumption of a building by a significant percentage compared with the pre-renovation levels, leading to a high energy performance" [EPDB 2012/27 EU]. An example of deep renovation within this thesis are the 2 scenarios utilised in section 4.3 ['E1' and 'E2']. The most ambitious level of renovation is the nZEB renovation which aims to contribute to energy savings of up to 70%.

A decision matrix is created below (tables 6.3-6.3.2) to assist stakeholders (designers and/or investors) in selecting various energy efficient measures and accompanying factors such as costs, and energy and emission savings. A decision matrix analysis is typically utilised when a decision should not be made based on one factor such as low costs but rather requires many different considerations to be taken int account.

The first step to creating a decision matrix is selection of a set of options and factors. The options in this case are the possible routes for a building to achieve the nZEB status. These have been listed in Table 6.3 as criteria 1-5 and have been created based on the government's suggested routes to achieving the future homes standard (as discussed in earlier chapters). Following this the factors that typically influence such a decision are selected and are as follows: energy savings, cost effectiveness/savings, and ease of implementation. The scores are then assigned for the different options based on the requirements/ambitions of the stakeholders. For this thesis two different scenarios assuming different priorities are described below to show how this would be implemented. Whereby, 0 = very unsuitable and 5 = very preferred for the various criteria and 0 = very unimportant and 5 = very important for the various factors. The next step involves multiplying each of the scores from Table 6.3.1 by the value/ weighting for relative importance of each factor shown in Table 6.3.2. This will give the weighted scores for each option/factor combination. Finally, these weighted scores are added up for each option. The option that scores the highest generally suggests that this is the most desired/ preferred route. If, it is then felt that the top scoring option is not the preferred one, then some more reflection on the scores and weightings applied may be required. This may be an indication that certain factors are more important to the stakeholder than initially thought.

Scenario 1: Main objective is to reach the nZEB standard with maximum energy savings and long-term low operational costs

Scenario 2: Main objective is to reach the nZEB standard with minimal capital investment and a quick payback

Table 6. 3: Routes to achieving energy efficiency/nZEB standard (nZEB criteria)

Criteria	Definition
Criteria 1	Significant fabric improvements; little HVAC improvements and undersized renewable/ microgeneration systems
Criteria 2	Small fabric improvements; assisted by significant HVAC improvements and renewable/ microgeneration systems [Government's preferred route]
Criteria 3	Very small fabric improvements; little HVAC improvements and significant renewable/ microgeneration systems
Criteria 4	Selective fabric improvements; combined with selective HVAC improvements renewable/ microgeneration systems
Criteria 5	Selective fabric improvements and renewable/ microgeneration systems; little HVAC improvements
Criteria 6	Selective fabric improvements and HVAC improvements; undersized renewable/ microgeneration systems

Table 6.3 1: nZEB decision matrix for scenario 1 and 2

	Energy Savings		Cost Savings		Ease of implementation	
Scenario	**1**	**2**	**1**	**2**	**1**	**2**
Criteria 1	2	1	2	1	4	1
Criteria 2	4	3	4	3	3	3
Criteria 3	2	5	4	5	2	4
Criteria 4	5	3	5	3	4	3
Criteria 5	3	2	3	1	3	2
Criteria 6	2	1	2	1	3	3

Table 6.3 2: nZEB decision matrix final scoring for scenario 1 and 2

	Energy Savings		Cost Savings		Ease of implementation		Scores	
Scenario	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
Weighting	**5**	**3**	**4**	**5**	**4**	**4**	-	-
Criteria 1	5x2→10	3	8	5	16	4	34	12
Criteria 2	20	9	16	15	12	12	48	36
Criteria 3	10	15	16	25	8	16	34	**56**
Criteria 4	25	9	20	15	16	12	**61**	36
Criteria 5	15	6	12	5	12	8	39	19
Criteria 6	10	3	8	5	12	12	30	23

For scenario 1 the criteria with highest score is criteria 4 followed by criteria 2. Meanwhile, for scenario 2 criteria 3 seems to be the most favourable as it has the highest score. As written above, scenario 1 had the objective of achieving the standard with maximum energy savings and long-term low operational costs. Meanwhile, for scenario 2 the goal was to retrofit with maximum cost savings and a quick payback. The criteria with the overall highest scores reflect these goals very clearly. For example, criteria four requires selective fabric improvements combined with selective HVAC improvements renewable/ microgeneration systems. This route ensures that an all-round retrofit is accomplished. The fabric improvements work to reduce the energy demand, the HVAC and renewable improvements work to optimise and offset the remaining energy consumption. Although this route does not lead to the lowest capital investment costs, it guarantees low operational energy costs meaning that goal of scenario 1 can be met via this route. On the other hand, criteria 3 which favours a very small fabric and HVAC improvements approach, but an oversized renewable/ microgeneration system ensures that capital costs are kept to a minimum. Renewable/ microgeneration systems have a quick payback period due to their significant energy savings. This approach will mean the standard is 'met' in terms of the PEC and CO_2 emission reductions. However, the energy demand of the building remains high and it continues to be an energy inefficient building.

This option with very small fabric improvements was included to reflect the real-life routes stakeholders currently take to achieve a seemingly energy efficient building. In fact, as discussed in the literature review some buildings undergo the 'nZEB' retrofit with no fabric improvements whatsoever. However, this approach is not the best solution moving forward. This is because although renewable energy is 'unlimited' the technologies we currently have are not as advanced as they could be and therefore would not be able to cope with our existing high demand. When a building is retrofitted to become nearly-zero using this 'no-fabric' approach they typically do so by relying on PV panels. In general, the Earth's surface receives enough solar energy to meet our existing energy consumption more than a thousand times over. However, the intermittence of solar energy depending on location makes this very difficult or almost impossible to achieve. To put this into perspective, the solar radiation reaching a sunny location like the south of Spain, adds up to about 1900 kWh/m^2/yr [Lopez, 2009]. That is equivalent to the energy contained in 1.2 barrels of petroleum. To fully rely on solar energy, it would need to be harvested in sunny deserts and transported around the world. This is currently unrealistic due to the already high costs of building photovoltaic cells which makes solar energy the most expensive of all renewable energies at present. Add to this the fact that the portion of solar energy on the surface of the photovoltaic cells that actually becomes electricity, is somewhere between 10%-20% shows the importance of firstly dealing with our energy demand rather than trying to offset the current high demand with reliance on what is considered infinite energy sources.

6.4. Design Variables

The CIBSE provide the industry with guidance via 'Technical Memoranda' (TMs). These focus on specific areas, such as building energy metering or natural ventilation in non-domestic buildings and offer in-depth technical guidance. CIBSE guidance TM38: Renewable Energy Sources for Buildings aims to help stakeholders identify the most appropriate low or zero carbon EEMs. It is accompanied by a decision support tool [See Appendix B]. The tool is a an excel based spreadsheet that is intended to assist stakeholders in identifying which design measures are most suited to their building. It allows users to select the building type, location, and apply a weighting to a small range of evaluation criteria. The tool then graphically pinpoints design measures which appear to be best suited to those requirements. In other words, it is very similar to the decision matrix above. This time, however, it is designed to assist stakeholders in deciding between alternative design measures as opposed to a particular retrofit approach.

The tool works in two stages*: "**Stage 1:** the opening sheet, which compares the likely relative performance of each technology against the criteria selected by the user. This analysis is based on rudimentary site information… **Stage 2:** a sheet for each technology, which further explores the feasibility of each technology and reassesses the information presented on the opening sheet. A limited amount of further information is required to allow each technology to be explored."*

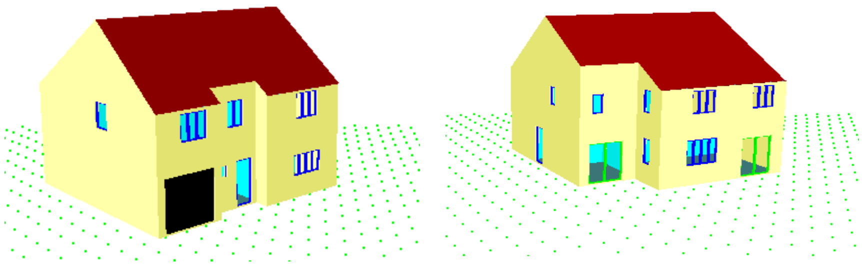
The technologies covered in the guidance are shown in Appendix C. The factors considered are CO_2 savings, cost effectiveness, and local impact. Table 6.4 extends the measures, factors, and type of building considered within CIBSE TM38 and is intended to be used in conjunction with the guidance document and the decision support tool. Like the decision matrix, stakeholders, oversee ranking of each factor on a scale of 0 to 5 (with 5 representing high importance).

The selected measures are all typically utilised measures not only in nZEB retrofit but also in all levels of building retrofit in general. They have been trialled throughout this work. The impact of the factors is categorised as Low [L]; Low-Medium [L-M]; Medium [M]; Medium-High [M-H]; High

[H] (following the same format as TM38). This is based on the general impact of the measures in the table and will always vary depending on the building type, climate, orientation, occupancy usage and behaviour and exact location.

6.5. Framework Validation

To validate the framework the first residential case study investigated in section 4.1 is utilised to show how the framework would work in practice. To start off, the 3D model of the case study is shown in Figure 6.2. Following the first generic framework presented in figures 6.1 and 6.2 it is noted that the following phases need to be considered initially: passive design, HVAC/DHW systems, incorporation of a renewable/microgeneration system. In addition, a cost analysis needs to be conducted and where possible monitoring of occupancy behaviour too. Finally, looking at Table 6.1 the aim to reduce the PEC and CO2 emissions to at least 75kWh/m^2/yr and 10KgCO_2/m^2, respectively.



4a) Front elevation   4b) Rear elevation

Figure 6. 2: Tas 3D Modelling results

Based on this the initial model is created and a PEC of 135.91 kWh/m^2/yr and CO_2 emissions of 51.73 KgCO_2/m^2 form the baseline for improvement. Linking this back to the investigation carried throughout sections 4.4-4.4.5 which follow the framework's recommended phases of investigations and areas of improvements, section 4.4.6 finally presents a nZEB that achieved a PEC of 43.27 kWh/m^2/yr and CO_2 emissions of 7.97 KgCO_2/m^2. However, once the cost analysis and the sensitivity analysis are conducted, the achieved PEC and CO_2 emissions are not financially the optimal solutions. Instead, it was found that the cost-optimal solution has a PEC of 75.5 $kWh/m^2/yr$.

This cost-optimal solution is purely based on modelling and best-practise work. The decision matrix therefore also plays an important role here. This can be used by the designer and/or investor and/or any other stakeholder involved in the decision either prior to beginning the investigation altogether or at this stage (once a cost-optimal solution has been established). Should the decision matrix be used to guide the retrofit scenarios before beginning the investigation, this would save time and will reduce the number of scenarios that need to be explored. However, it does limit the types of scenarios explored which might lead to certain compatible and cost-effective packages to be excluded from the selection process.

On the other hand, as showcased in section 6.3 'scenario 1 and 2' the criteria with the highest score will give an indication of what is important and preferable to the stakeholders. Based on this the cost-optimal scenario can be looked at and altered to suit the preferred criteria. The evaluated design variables in Table 6.4 can then be used to quickly alter the scenarios quickly and with minimal effort, as required and based on which criteria was selected by the decision matrix. The end product will be a nZEB that is energy and cost efficient in the long-term. However, as discussed earlier post-occupancy evaluation also forms a necessary part of this process.

6.6. Chapter Summary

The chapter established a generic framework, a detailed framework and a decision matrix that will act as a tool to help reaching the nZEB standard. The frameworks were validated by using an example case study to showcase how they would work in practise. This chapter ties in all the investigations carried out in chapter 4 and 5 and provides a set of final recommendations as to which nZEB route should be taken; which building elements require focus; and which specific design variables offer the most benefit, either in terms of economic benefits or energy benefits or a combination of the two. Furthermore, the definitions that were aggregated from the literature review were altered and finalised based on the cost-optimal calculations carried out in chapters 4 and 5.

Table 6. 4: Overview of the impact of the EEMs investigated throughout this work

Technology	Energy Savings		CO_2 Savings		Cost effectiveness		Ease of implementation		Overall Suitability	
	Residential	Commercial	Residential	Commercial	Residential	Commercial	Residential	Commercial	**Residential**	**Commercial**
Photovoltaics[1]	M-H	M-H*	M	M	M	L-M	L-M	L-M	**M**	**M**
Solar thermal[2]	M-H	M-H	M	M	L-M	M	L-M	L-M	**M**	**M**
CHP [Gas][3]	L-M	L-M	M	L-M	M	M-H	L-M	M	**L-M**	**M-H**
CHP [Biomass][3a]	M-H	M-H	M	M-H	M	M-H	L-M	M	**L-M**	**L-M**
CCHP [Gas][4]	M-H	M-H	M	M	L	L	L	M	**L**	**L-M**
CCHP [Biomass][4a]	L	M-H	M	M	L	L	L	M	**L**	**L-M**
Ground source heat pump[5]	M-H	M-H	M	M	L-M	M	L	L-M	**M**	**M-H**
Wind power[6]	L-M	L-H	L-M	M	L	L-M	L	L-M	**L**	**L-M**
Biomass Boiler[7]	H	H	M-H	M-H	M	M	M-L	M-H	**M**	**M-H**
Double glazing[8]	L	L	L	L	L	L	M-H	M-H	**M**	**M**
Triple glazing[8a]	L	L	L	L	L	L	M-H	M-H	**M**	**M**
Mechanical ventilation [with heat recovery][9]	L	L	L	L	L-M	L-M	H	H	**M**	**M**
LED lighting[10]	L	L	L	L	H	H	H	H	**M**	**M**
LED with auto-sensor[10a]	L	L	L	L	L	H	L	L-M	**L**	**L-M**

Low [L]; Low-Medium [L-M]; Medium [M]; Medium-High [M-H]; High [H]

[1&2] full potential will be realised if the building has good access to solar radiation (e.g. houses surrounded by tall apartment buildings that cast shadows will not benefit).

[3/a] should be used with buildings with constant heating demand to obtain maximum efficiency/savings

[4/a] should be used with buildings with constant heating and substantial cooling demand to obtain maximum efficiency/savings

[5] usage depends on space, geology, and aquifer availability. Should be used with buildings with substantial heating demand and high occupancy rate to obtain maximum efficiency/savings

[6] ideal for use in rural environments. Can be used in urban locations on rooftops. Energy produced will be dependent on weather conditions

[7] ample space is required for storage. Biomass boilers can significantly increase the total of PM, PAHS, and dioxins if used on a national scale.

[8] 80% of UK buildings have double glazing [BRE, 2018].

[9] if existing building has poor insulation, incorporating just

[10/a] auto-sensors will be suitable in commercial buildings such as offices, schools, hospitals and factories. They can be potentially utilised in certain public areas within hotels. Within a residential setting this will depend on occupier but can be suitable for usage outside the home, in gardens, and in common areas in apartment buildings.

Chapter 7: Conclusion

7. Summary of Work

This work presented various residential and commercial building case studies. Using computational fluid dynamic software, Tas Edsl, the energy performance of the buildings as they currently stand was examined and validated against the actual building energy consumption, where possible.

The research questions outlined in the beginning have all been addressed throughout this work. Below is a summary of the findings.

1) **What are the types of EEMs that could be realistically applied to reduce the energy consumption in commercial and residential buildings?**

'Energy efficiency' in buildings refers to the degree to which the energy consumption (kWh/m^2/yr) corresponds to the building regulations for that building (residential or commercial) under certain climatic conditions. The current standards within the UK are essentially representative values for various types of buildings. These standards and regulations have been aggregated over many years by analysing data on the current building performance. They are continually evolving and typically represent a median level of performance. The 'Good Practice' standards represent the top performing buildings. nZEBs and other high performing buildings would therefore fall into that category.

Regardless of whether a building is residential or commercial the energy use factors remain the same. As discussed previously these factors are heating (and cooling depending on climate), hot water, lighting, ventilation, and auxiliary energy needed for fans, pumps etc.

Investigating different residential and commercial buildings has shown that different measures work best with different buildings depending on the building type, cooling, heating needs, occupancy type, hours and existing building systems and components. For example, a SWH system underperformed in a building with constant heating and cooling needs throughout the year. On the other hand, the same system performed very well when incorporated in buildings with high heating demand.

To select the most suitable EEM the energy usage breakdown should therefore be initially assessed. This allows the designer to determine which areas are contributing to most of the energy demand and therefore which areas require focus/ improvement. Within this thesis it was found that generally for the investigated buildings all the energy use indicators listed above required an improvement in order to reach the nZEB standard. This question was therefore explored on an individual basis for each case study investigated and the recommendations can be found throughout chapters 4 and 5. In addition to this, Section 6.3 provides the impact of the EEMs investigated throughout this work in terms of energy savings, CO_2 savings, cost-effectiveness, ease of implementation, along with the overall suitability for both residential and commercial buildings.

2) **To what extent is the residential and commercial nZEB retrofit technically and economically feasible?**

The concept behind a nZEB means that it is a low energy demand building complimented by renewable/microgeneration systems. The choice to focus on existing residential and commercial buildings is because existing buildings make up most of the UK's building stock. Furthermore, existing buildings have certain limitations (as discussed in the literature review) thereby presenting a bigger challenge.

All buildings investigated prove that the nZEB retrofit is technically feasible. The selection and number of EEMs may vary significantly from one building to the next. However, with suitable and careful analysis of the baseline building and consideration of the heating and cooling demand throughout the year ensures that the nZEB targets are met.

The results of the first case study show that to successfully retrofit an existing dwelling it is necessary that the designer does not only consider the inclusion of renewables and neglect building fabric improvements and vice versa.

It is also clear that the nZEB standard can indeed be achieved for older UK hotel buildings. Based on the results of Edinburgh Grosvenor hotel, it can be concluded that prioritising improving the energy efficiency of the building and then adding a renewable/microgeneration system is the best approach to retrofit a building located in a cold-dominant climate. In this way the thermal losses because of an energy inefficient building envelope is lowered which in turn drastically lowers the energy demand of the building. This is in consonance with the requirements set by the EU directive which stipulates that nZEB buildings are to have 'very low energy needs.' Thereafter, the incorporation of a renewable/microgeneration measure will then act as an additional provision to finally lower the energy consumption, PEC and CO_2 emissions to meet the standard.

In terms of financial feasibility, the case studies assessed demonstrated that there is a gap between the current vision for what is a nZEB and the cost-optimal solutions calculated within this work. This is in agreement with the findings from the literature. Although majority of LCC nZEB studies have been conducted in other countries, there seems to be a common trend amongst these studies whereby the nZEB standard PEC level is stricter than the cost-optimal solution's PEC level. One of the simplest and quickest ways to bridge this gap would be to improve the rates for the currently available incentive schemes and possibly introduce new ones to further support the economic feasibility of the nZEB standard. Nevertheless, the cost-optimal solutions identified within the work offered considerable reductions in the primary energy consumption and global costs in comparison to the baseline scenarios.

To increase the reliability of the cost calculation a homogeneous database for such UK retrofit projects is necessary. When this occurs, the specific cost results of such studies can be applicable to many buildings of similar stock. A comprehensive and applicable database requires several phases to be successfully utilised and will need to be defined based on location too as this can greatly affect the cost of measures.

3) **What are the impacts of a changing climate on an achieved nZEB energy performance? And how does this affect the financial viability of the investment?**

The investigations carried out through this thesis demonstrate how buildings can be vulnerable to climate change. In the UK, the replacement rate of buildings is low, and the lifetime is long, therefore, much of the existing building stock will be affected by changes in the climate. Moreover, majority of current UK buildings are designed to operate for the current temperate maritime climate. As the number of extreme weather events is increasing each year buildings should ideally be able to operate over a range of climatic conditions with minimal fluctuations to the energy consumption.

As shown throughout chapters 4 and 5 the heating demand is the largest contributor to energy consumption for all buildings investigated. The simulations under future climatic conditions however demonstrated that the heating demand remains high and the cooling demand significantly increases leading to an overall drastic increase in the energy consumption. Consequently, the energy costs increased and unfortunately, the net savings for the nZEB retrofit decreased. It is therefore vital that a sensitivity analysis of a similar nature is carried out to ensure that the achieved nZEB standard is maintained under varying climatic conditions. This will in turn ensure that the solution's investment remains as projected.

Costs of measures included in this thesis are projected to decrease in the future while their efficiency is expected to increase. These factors should make achieving a nZEB less challenging and more economical.

The data and solutions presented throughout chapters 4 and 5 need to be continually reviewed and updated as weather data projections develop and improve in accuracy as it may lead to designers adopting unsuitable solutions for the future. Currently, there are no official regulations that provide recommendations for buildings to be retrofitted to also adapt in order to withstand extreme weather events. This needs to change in the future to protect people and properties from any potential damage, loss of life, and discomfort that may arise as a result of climate change. Clear guidelines should be available for stakeholders and designers.

4) To what extent does retrofitting a building to the nZEB standard increase the occurrence and severity of overheating?

There are many different types of climate risks that could potentially affect buildings such as flooding (inland and/or coastal), cyclones, and overheating. The mitigation strategies utilised will differ depending on the risk being investigated. Although UK properties can be at risk of flooding these properties are typically located near the coast, riverside, or on a floodplain. None of the properties investigated within this thesis are at risk of flooding and this was therefore not considered.

The answer to the previous research question gave an insight into the potential the nZEB standard has in increasing the risk of overheating. However, the extent of this was only truly quantified once a full analysis was conducted with the retirement village.

Severe overheating was experienced under the 2050s and 2080s weather projections for the nZEB scenario in comparison to the base case. The incorporation of CCHP as a possible solution to reaching the nZEB standard and maintaining thermal comfort was demonstrated by the results. The Reading hotel case study demonstrated that selection of a CHP or a CCHP system will depend on several factors, in particular, the heating and cooling demand of the building. A CHP system is more appropriate and should be incorporated in a building with considerable heating demand and moderate/no cooling demand. On the other hand, a CCHP system is more appropriate in applications with equally considerable heating and cooling demands, and it is essential that the cooling demand is not omitted.

It can be concluded that in line with the current paradigm that favours energy efficiency, the associated risk of increasing overheating cannot be ignored due to the numerous negative consequences associated with this. Whilst carrying out energy efficient retrofitting of properties may be necessary to aid in the transition towards an energy sustainable future the design choices and recommendations may need to be reconsidered so that the building continues to perform under variable weather conditions. Thus, integrating mitigation strategies in energy efficient retrofit is necessary. Most importantly, retrofitting with a focus on only adapting to hotter weather conditions is not a viable solution as it may lead to a substantial increase in heating demand during the heating season. Energy efficient retrofit projects should therefore, ideally, find a balance between meeting the heating and cooling demands of the building in an energy efficient way under current and future weather conditions.

The analysis of existing literature revealed that residential and commercial nZEBs still have a way to go before they are fully established in terms of their definition and methodology. Commercial nZEBs in particular still lack a robust definition and analyses.

In this respect, all research answers summarised in the above paragraphs offer original research contributions of this PhD which aims to provide a better understanding of how to achieve the nZEB standard and the risks associated for both residential and commercial UK buildings. The applicable frameworks (including the decision matrix) developed to analyse and guide the attainment of the nZEB standards for UK buildings is an original outcome of the analysis.

When it comes to retrofitting, in practice, the retrofit measures and selected adaptations will always depend on the available budget and the client's willingness to invest in such options. Therefore, it is essential that the designer and design team, work with clients to ensure they understand the long-term environmental and financial benefits of choosing to adapt their building. Furthermore, it is crucial that the client's requirements, objectives and limitations are fully understood to ensure that acceptance and adoption of the proposed solution is assured. Without client awareness to the benefits and risks the full potential of the nZEB standard will not be realised and uptake will be impeded. Although the case studies illustrated are all real buildings, the retrofitting recommendations provided are primarily based on best practice from an energy efficiency point of view. Where costs have been considered and a cost-optimal solution selected it is also based on best practice. Therefore, 'real-life' constraints such as client requirements, time and budget restraints were not overriding factors.

The outcomes of this research should further encourage the retrofitting of existing buildings with high energy efficiency standards such as the nZEB standard. With careful and thorough design decisions that firstly work to lower the energy demand of the building and that consider the building resilience to a potentially different climate in the future, the standard can be achieved with long-term cost and energy benefits.

7.1. Research contribution

7.1.1. Theoretical Contributions

Several residential and commercial case studies are utilised to explore what it means to achieve the nZEB standard and apply it to existing UK buildings. The highlighted outcomes demonstrate that with well thought-out design decisions and careful consideration of a building's resilience to a changing climate, the standard can be achieved — and this can introduce long-term cost and energy benefits. There is a large amount of work that needs to be done, and many questions to be answered, before fully transitioning to nZEBs. The summary of the theoretical contributions is highlighted below as addition to the summary of work.

The case studies presented offer differing approaches to reaching the nZEB standard. Each case study focuses on presenting a set of recommendations for a specific residential or commercial building of a certain stock. Whilst there are significant benefits — especially environmental benefits — associated with implementing the nZEB standard, the risks and complexities must be noted and addressed through careful design measures. The risks (namely, the cost-benefit relationship; the building resilience to future climatic conditions; and the potential risk of overheating) are highlighted in different ways in each of the case studies, and possible solutions are offered.

In each case study the primary energy consumption and carbon emissions are reduced by more than 60%. Should the implementation of such retrofit strategies become widespread this will be the first step to addressing the energy debt that is associated with most existing buildings, thereby contributing towards tackling some of our current environmental challenges.

The need to find a balance between conserving energy and heat during the heating season and keeping the building cool during the non-heating season can be a key barrier to retrofitting the building to the required standard. This issue is particularly applicable to existing buildings due to lack of control over the potentially poor initial design choices that can contribute to

Whilst there are significant benefits, especially environmental benefits, associated with implementing the nZEB standard, the risks and complexities must be noted and addressed. The risks, namely, the cost-benefit relationship; the building resilience to future climatic conditions; and the potential risk of overheating are highlighted in different ways in each of the case studies and possible solutions are offered.

When it comes to retrofitting, in practice, the retrofit measures and selected adaptations will always depend on the available budget and the client's willingness to invest in such options. Therefore, it is essential that the designer and design team, work with clients to ensure they understand the long-term environmental and financial benefits of choosing to adapt their building. Furthermore, it is crucial that the client's requirements, objectives, and limitations are fully understood to ensure that acceptance and adoption of the proposed solution is assured. Without client awareness to the benefits and risks the full potential of the nZEB standard will not be realised and uptake will be impeded. The final nZEB solution should ideally represent the best combination of the energy and cost performance. A balance between the two is necessary. A focus on just lowering the costs will mean the nZEB requirements are not met. Likewise, a focus on just meeting the nZEB standard with the current level and cost of technology will render the solution economically unfeasible. Consequently, the nZEB standard provides improved environmental outcomes, whilst ensuring profitability. The potential for cost savings due to substantial operational energy savings should be highlighted to stakeholders and steer adoption and compliance.

The published work arising from this thesis forms several theoretical contributions. Published work 1 on the list of publications for this work contributed to chapter 5, section 5.5 whereby a typical UK hotel was presented and an nZEB investigation carried out alongside a LCCA. Moving on the next published work on the list (2.) this paper contributed to formulation of chapter 4, section 4.5. This focussed on presenting a detailed LCCA of various retrofit solutions and identifying a cost-optimal solution for a typical UK house. Paper 3 on the list contributed to chapter 5, section 5.3. This established that achieving the nZEB standard was indeed feasible for a historical commercial building type such as Edinburgh Grosvenor. Papers 4, 5, and 6 contributed to chapters 4 and 5 sections 4.8, 5.1, and 4.1, respectively. Paper 4 presented the risks associated with achieving the nZEB standard, namely, the overheating risk. This was explored through a retirement village where the population demographic were vulnerable and behavioural changes could not be implemented. Paper 5 explored the benefits and potential of incorporating C/CHP systems in building retrofits. Finally, paper 6 confirmed that the nZEB standard is achievable for a typical UK house with an existing poor envelope, although several measures were necessary.

Transitioning into low carbon and low energy buildings should ensure that the costs of such technologies continues to decrease. Furthermore, it is strongly recommended that once retrofitted buildings are monitored to assess performance of not only occupant behaviour and its impacts but also how the building performance varies between the heating and non-heating season. This should allow the building designers to pick up on any initial concerns that may need to be addressed.

7.1.2.Practical Contributions

In addition to the contribution to the literature by publishing papers, the outcomes and recommendations of this thesis have already started making positive impact on the built environment through a research insight document that was published by CIBSE in August 2020.

This document presented a method for applying the nearly-zero energy building (nZEB) standard to existing UK commercial and residential buildings. The findings presented were based on analysis supported by dynamic simulation modelling of UK buildings, aiming to demonstrate the potential benefits but also highlight the risks associated with achieving such high energy-efficiency standards within the built environment.

The work built on that presented in TM55: Design for future climate — case studies (CIBSE, 2014). Four case studies (two residential and two commercial buildings) were utilised to establish a methodology for reaching the nZEB standard. These were presented individually within the publication to focus on the various outcomes of each building type.

The scenarios summarised suggested a methodology regarding how the nZEB standard may be achieved and applied to existing residential and commercial buildings of the same stock. In each case study, the primary energy consumption and carbon emissions were reduced by more than 60%. Should the implementation of such retrofit strategies become widespread, this would be the first step to addressing the energy debt associated with most existing buildings, thereby contributing towards tackling some of the environmental challenges we currently face.

The focus on selecting nearly-zero solutions that are also cost effective should encourage adoption of these. However, as mentioned previously, this cost-effective solution will depend on client budget, requirements and ambitions. Nonetheless, the potential for cost savings due to substantial operational energy savings should be highlighted to stakeholders and could steer adoption and compliance.

The project used dynamic simulation modelling not only to check the primary energy consumption, carbon emissions, etc., but also as a tool for designing and shaping the retrofit scenarios. The buildings were modelled firstly as a baseline, then with individual energy-efficient measures, and finally as a complete retrofit combining all energy-efficient measures. In this way, it was possible to assess a wide range of potential scenarios before selecting the best option in terms of energy and cost benefits.

One of the main challenges involved with reaching the nZEB standard is the compilation of life-cycle costs. This is mostly due to the large number of components associated, and the lack of an official database; it was recommended that the introduction of an official database would tackle this challenge and help standardise approaches to reaching the standard with financial benefits.

Physical and legal constraints (such as conservation areas and listed buildings consent) are some of the key limitations to the implementation of energy-efficient measures. The case studies however showed that with careful consideration the nZEB standard can be achieved with fabric improvements and the inclusion of renewables.

Overall, the outcomes demonstrated that with carefully thought-out design decisions that consider the building resilience to a changing climate the standard can be achieved with long-term cost and energy benefits. Additionally, the research results established that retrofitting of existing buildings can provide sizeable economic benefits.

7.2. Research Limitations and Future Work

This dissertation proposes some of the first steps (and cautions) towards the effective inclusion of nZEBs within the current UK building stock. Thus, all findings require further research, to develop and be utilised as full methodologies that make up a part of the UK's building regulations.

The main limitation of this thesis is that despite all the step taken to ensure that the performance gap is small, in the end it must be acknowledged that this is something that cannot be eliminated with currently available software. Although the thesis did investigate the potential impact of occupant behaviour on the performance gap this is not the focus of the thesis. Instead it only intends to raise awareness of the potential negative consequences this may have on investments of nZEBs which are typically based on energy estimation during the design stage. The modelling and simulation as used in this work is to evaluate how buildings can reach the nZEB through various design strategies and to address issues involving climate change potentially affecting the achieved performance of the buildings. This work should therefore be extended in the future by focussing primarily on the performance gap and how this can be closed and the exact factors which contribute to the gap and therefore need to be controlled. For this to be done effectively the work will need to focus on the monitoring of nZEBs post-occupancy.

Moreover, there is also a limitation related to the types of buildings utilised throughout this thesis, as discussed in earlier sections. The work would benefit from investigating a wider range of residential and commercial buildings, such as, high-rise (<10 storeys) residential buildings and other types of commercial buildings such as schools, offices, and hospitals. A focus on achieving the standard with cost benefits for public buildings such as schools and hospitals can bring about many long-term societal benefits.

The selected EEMs and retrofit scenarios throughout this thesis were selected by the author without any limitations, other than the technical feasibility and applicability of the measures to the relative building type and its location. Although the methodology and steps utilised could all be followed by a designer to achieve the nZEB standard, in real-life applications investor input is likely to play a huge part. A potential area for further research could therefore focus on investigating the impact investor decisions has on achieving the standard. This would require a large sample of buildings with various investors and designers who are willing to share their experience through surveys or interviews. Furthermore, increased research effort is needed to understand what exactly is required to encourage and increase the market uptake of nZEBs. The many stakeholders involved in such legislations makes it difficult to pinpoint why uptake is slow. One possibility could be the lack of regulations/ support from authorities in the first place. On the other hand, lack of understanding and knowledge about retrofit technologies, the nZEB standard, and the associated costs could also play a huge part.

Finally, although the investigations conducted throughout this thesis aim to find solutions specifically for UK buildings, the steps and methodology applied can and should be replicated in different countries. The EPBD requires each country to come up with their own unique and suitable definition due to reasons discussed throughout the work. However, the methodology utilised can be used to come up with varying definitions with very minor alterations required to the methodology. More specifically, the weather files utilised would be completely different and the thermal analysis simulation and LCC software can be changed to comply with the relevant building regulations of the country.

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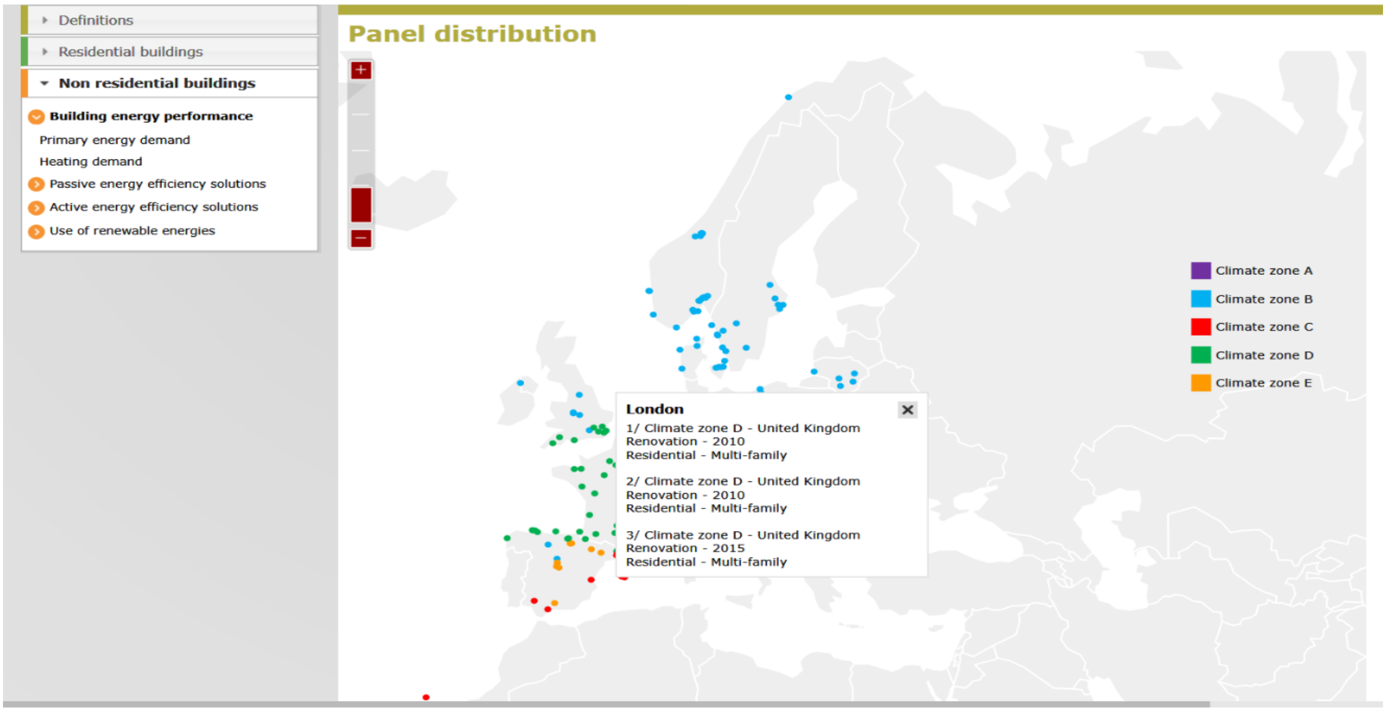
Appendix

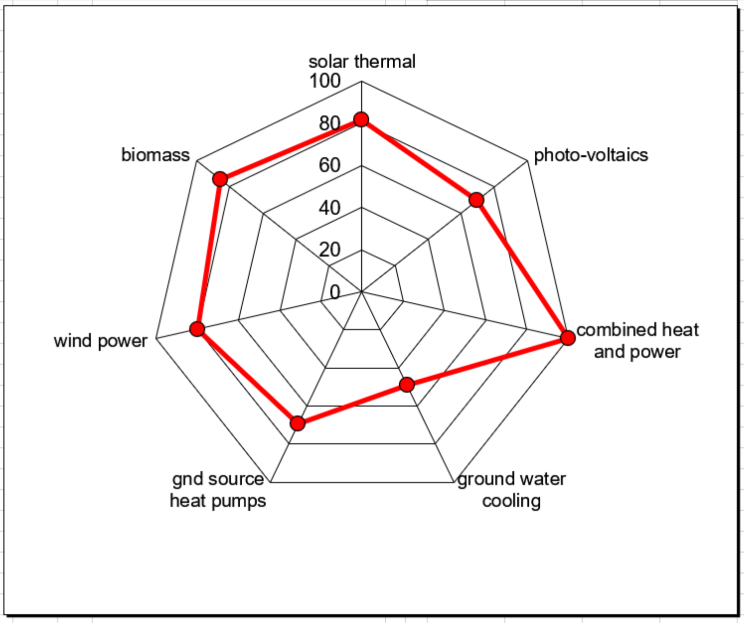
Appendix A



Appendix B

Building Information	
Type	**mixed use developments**
Location	**suburban**
Exposure	**normal**

Ranking	
Cost Effectiveness:	**4**
Carbon Savings:	**5**
Marketing / Image:	**2**
Technology Risk:	**3**



Appendix C

Table 4.1 Overview of LZC technologies

Technology	Carbon dioxide savings	Cost effectiveness	Local impact
Solar thermal systems	Low-medium	Medium	Low-medium
Photovoltaics	Low	Low	Low
District heating and cooling	Medium-high	Medium	Low
CHP, fulled by:			
— gas	Medium	Medium	Low-medium
— biomass	Medium-high	Medium	Low-medium
Ground water cooling	Depends on building type	Depends on building type	Low
Ground source heat pumps	Medium	Medium	Low
Wind power	Low-medium	Medium	Medium-high
Biomass boiler	High	Medium	Medium